A COMPARATIVE STUDY OF UASB AND MODIFIED UASB REACTORS TREATING LOW STRENGTH DOMESTIC WASTEWATER

A Thesis Submitted in Partial
Fulfilment of the Requirements
for the Degree of
Master of Technology
by

Nitin A. Gawande

Department of Civil Engineering
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

April, 1996

CERTIFICATE

It is certified that the work contained in the thesis **"A Comparative Study of UASB and Modified UASB Reactors Treating Low Strength Domestic Wastewater"**, by *Nitin A. Gawande*, has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

Cvenkobachar 15.4.96

C. Venkobachar
Professor
Department of Civil Engg.
Indian Institute of Technology
Kanpur.

April, 1996

ACKNOWLEDGEMENTS

I express my deep sense of gratitude to my professor and guide Dr. C. Venkobachar. His deep involvement in my thesis work, right from inception upto the successful completion made this thesis a enjoyable task. I am highly thankful to Dr. C. Venkobachar and his family members for the care taken during my ill health. I remain indebted with their courtesy.

I express my respect and gratitude to Dr. Malay Chaudhuri for his help during the course work. I thank him for his encouragement for the experimental works.

I express my respect and gratitude to Dr. Vinod Tare and Dr. D.K. Ghosh for their help extended to me during the course work.

I am thankful to Dr. Mrs. Leela Iyengar for her help during my experimental study. The discussions involved with her provided me a better understanding of the subject. I express my sincere gratitude to her.

I am highly thankful to Mr. M.G. Grasius (Grasius sir) for providing me the ready platform for my experimental study. Without his valuable suggestions and help this was not so easy task. I express my sincere gratitude to him.

I am thankful to the laboratory members of Dr. D. Kunzru for the help extended during the use of gas chromatograph.

I am thankful to the Institute Works Department for getting the wastewater from the pump house regularly.

The cooperation extended by the staff of environmental engineering laboratory is worth appreciation.

I am highly thankful for the help and valuable suggestions by Ms. Ligy Philip, Mr. Siby John, Mr. P.K. Singh and Mr. M. Javed.

I thank Parveen Goel, Anupam Kansal and Ashutosh Mishra for helping me throughout my stay here.

My thanks are due to my friends of B-bot and Ghat-mandal who made my life cheerful during my stay in the campus.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

This study was conducted to compare the performance of laboratory scale Upflow Anaerobic Sludge Blanket (UASB) reactor and a modified UASB reactor, incorporating the tube settlers in the settler zone for the treatment of low strength domestic wastewater from the campus of I.I.T. Kanpur. The sewage had average BOD of 41 mg/L and COD of 172 mg/L. The reactors were inoculated with pregranulated sludge. The reactors were run at the ambient temperature which was ranging from 16 to 23 °C during experimental period of 131 days. The experimental study consisted of a number of steady-state continuous runs with hydraulic retention times ranging from 6 h to 1.5 h. The primary start-up period was curtailed due to the use of pregranulated biomass. Both the reactors performed satisfactorily at HRTs of 6 h and 3 h, meeting the standards for direct disposal into inland waters. The modified UASB reactor showed better removal at these HRTs. Washout of granular biomass occured in the conventional UASB reactor at HRT of 2 h. Hence this reactor was stopped after the 2 h run. The modified reactor performed well at 2 h meeting the BOD requirements. The tube settlers in modified reactor showed better capture of TSS than the UASB reactor. Further the modified reactor showed better COD(total and soluble) removal at HRT of 1.5 h due to expansion of sludge bed. The effluent BOD was 26 mg/L whereas the TSS removal was low. The high TSS escaping out of reactor is expected to be reduced with prolonged operation. The biomass from both the reactors showed appreciable increase in the specific methanogenic activity values. The modified UASB reactor can be used as a package unit for treatment of low strength domestic wastewater without post-treatment.

1. INTRODUCTION

The increasing needs of human civilisation is exerting a heavy pressure on the natural resources and ultimately heading towards the ecological crisis. The environmental pollution of rivers due to indiscriminate disposal of domestic and industrial wastewaters into inland water is one of the major concerns of the Indian Government. Hence Ganga Action Plan to undertake the manmoth task of cleaning river Ganga was launched with an objective to develop appropriate technology to treat the wastewater and also to disseminate this information. Ganga Action Plan Phase -I had just now been completed. To a large extent it had been able to intercept and divert the wastewater reaching the rivers in major towns like Rishikesh, Haridwar, Kanpur, Allahabad, Varanasi, Patna etc. The diverted wastewater after proper treatment is discharged either on land or to river Ganga.

Several alternative treatment systems like aerobic and anaerobic are available for this purpose. One of the main issues that should be addressed is the requirement of electrical energy for the treatment of wastewater. Towards this the anaerobic treatment systems have an edge over the aerobic processes, as these are less energy intensive. The earlier versions of anaerobic systems, however, demanded large detention times and hence high volumes, thus increasing the capital cost. Further, the slow growing methanogens were posing considerable problems. Due to better understanding of microbiology and biochemistry of microbial consortia involved in anaerobic degradation coupled with

the advent of high rate anaerobic systems in last two decades, these are now enjoying the customers confidence better than previous versions. As a result they are gaining popularity in treatment of various industrial effluents from sugar and starch industries, breweries, paper mills etc. Production of energy rich methane has made this processes as least energy consuming process.

The Upflow Anaerobic Sludge Blanket (UASB) reactor, one of the high rate reactors, is capable of retaining high concentration of biomass. In UASB, the granular sludge is produced which does not require additional supporting media. Hence it becomes an obvious choice of treatment of wastewater. The application of UASB for domestic wastewater under tropical climatic conditions was studied by Lettinga *et al.* (1981). Encouraged by the efficient performance of UASB in Europe, a demonstration UASB plant of 5 MLD capacity has been set up at Jajmau, Kanpur in 1989 under Kanpur Indo-Dutch Sanitation project to examine its feasibility to treat domestic wastewater. The BOD removals by this plant was 75-80 %. However, due to non-compliance of effluent to the standards, a post-treatment in the form of one day detention time oxidation pond was incorporated. The satisfactory performance of this plant has resulted in installing a 14 MLD UASB plant at Mirzapur to treat dilute domestic wastewater and 36 MLD plant at Jajmau to treat combined tannery and domestic wastewaters. Incorporation of oxidation pond requires more surface area and hence there is a need to examine other alternatives.

The objective of the present study is hence, directed towards,

1) To modify the configuration of UASB reactor such that there is no need of separate post-treatment and compare its performance with the conventional UASB reactor.
2) Feasibility of using the pregranulated sludge to treat dilute domestic wastewater.

2. LITERATURE REVIEW

The adverse impacts of disposal of domestic wastewater on environment and concern to public health are well known. The primary objective of sewage treatment includes the reduction of the concentrations of the four most important constituents namely, (1) suspended solids, (2) organic (biodegradable) solids, (3) nutrients and (4) pathogenic organisms. The following sections deals with various treatment options with special reference to anaerobic processes.

2.1 Treatment Options

Wastewater treatment process can be divided into biological, physical, chemical and physicochemical methods. Amongst the biological processes, one can distinguish the difference between aerobic and anaerobic processes. A schematic comparison of aerobic and anaerobic wastewater treatment is given in Figure 2.1, (Mergaert *et al.*, 1992).

The anaerobic treatment has the following main advantages :

1. Less sludge production.
2. Less energy requirement.
3. Removal of some compounds (e.g. chlorinated organics) which the aerobic processes are reported to be not capable of removal.
4. Energy recovery in the form of methane.
5. Anaerobic sludge can be preserved for long durations without serious deterioration.

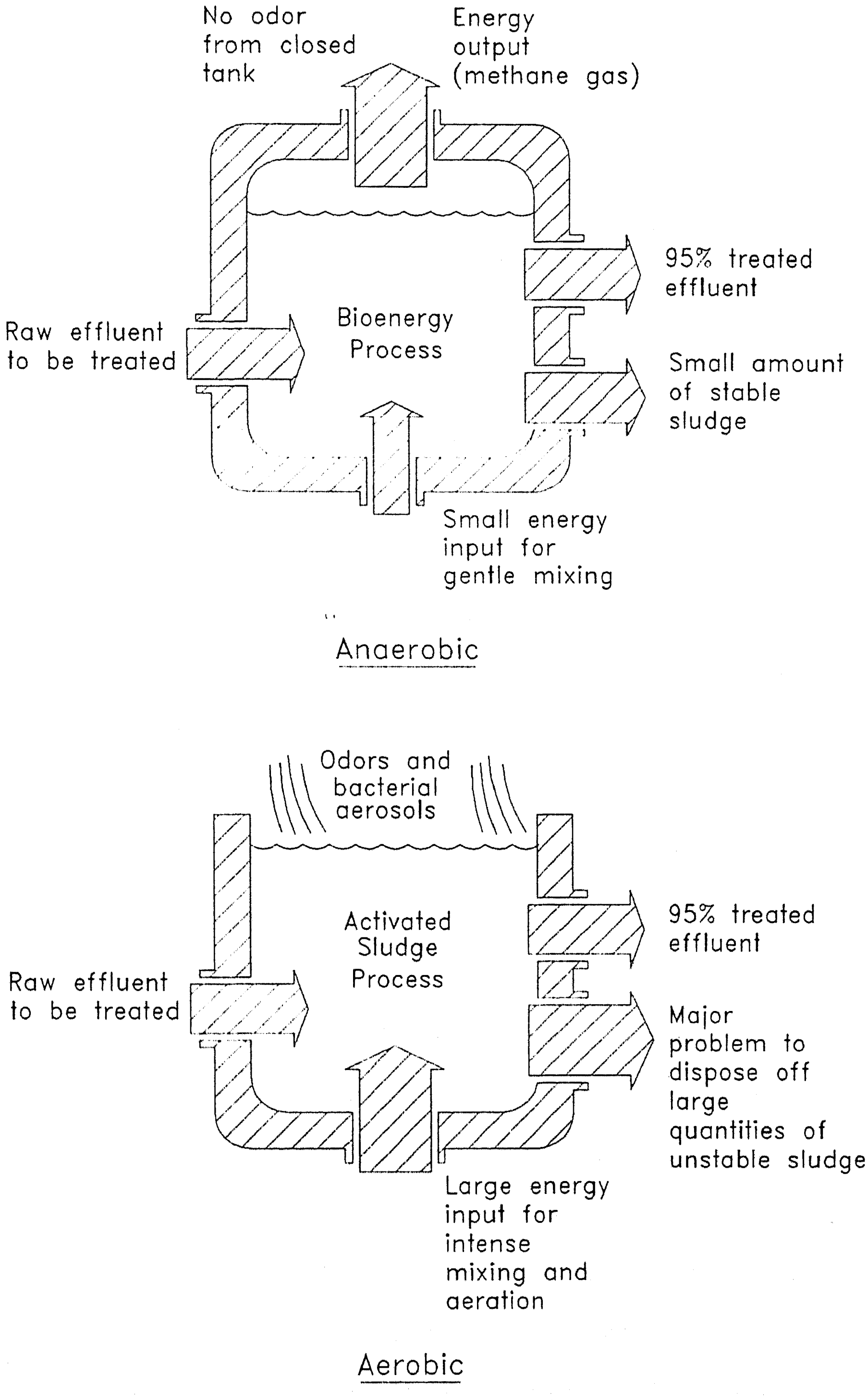


Fig. 2.1 Comparison of anaerobic and aerobic wastewater treatment processes (Mergaert *et al.*, 1992)

However, this process has some disadvantages such as,

1. Anaerobic bacteria (particularly methanogens) are highly sensitive and prone to inhibition by toxic compounds.
2. Anaerobic treatment normally demands an adequate post treatment for removal of residual BOD, ammonia, malodorous compounds etc.

2.2 Anaerobic Treatment Process

2.2.1 Fundamentals of Anaerobic Process

Anaerobic digestion is a fermentative process of special interest for wastewater treatment. This fermentative catabolism involves conversion of organic matter to methane and carbon dioxide in the absence of molecular oxygen. The electrons produced during degradation of organic matter are accepted by organic compounds. The process is mediated by different groups of facultative and obligate anaerobic organisms. Anaerobic digestion of complex organic materials can be divided into seven subprocesses following the reaction scheme suggested by Gujer and Zehnder (1983). They are as follows:

1. Hydrolysis of complex, particulate organic matter.
2. Fermentation of amino acids and sugars.
3. Anaerobic oxidation of long chain fatty acids and alcohols.
4. Anaerobic oxidation of intermediary products (such as short-chain fatty acids, except acetate)
5. Conversion of hydrogen and carbon dioxide to acetate (homoacetogenesis).
6. Conversion of acetate to methane (acetoclastic methanogens).
7. Methane production by reduction of carbon dioxide (reductive

methanogenesis).

The major group of organisms involved are (1) fermentative bacteria, (2) hydrogen producing acetogenic bacteria, (3) hydrogen consuming acetogenic bacteria and (4) acetoclastic methanogenic bacteria (Pavlostathis and Gomez, 1991). The pathway of anaerobic process is presented in Figure 2.2.

2.2.2 Anaerobic Treatment Systems

The classical anaerobic treatment systems include standard rate stratified anaerobic digestor without mixing and having a hydraulic retention time of 30-40 days. The high rate anaerobic reactors are employed widely now-a-days for treatment of wastewater. A description high rate digestors are presented below.

2.2.2.1 High Rate Anaerobic Systems

A breakthrough in design of anaerobic treatment systems came about with the development of modern or high rate systems. These reactors are characterised with high sludge retention. Figure 2.3 shows configurations of various reactors. The two basic mechanisms of sludge retention are employed in such reactors. They are

1. System based on immobilisation, attachment on a solid carrier material. The downflow or upflow anaerobic filter, granular and fluidised bed reactors fall in this category.
2. System based on solid-liquid separation. The contact process and the Upflow Anaerobic Sludge Blanket reactors belong to this category.

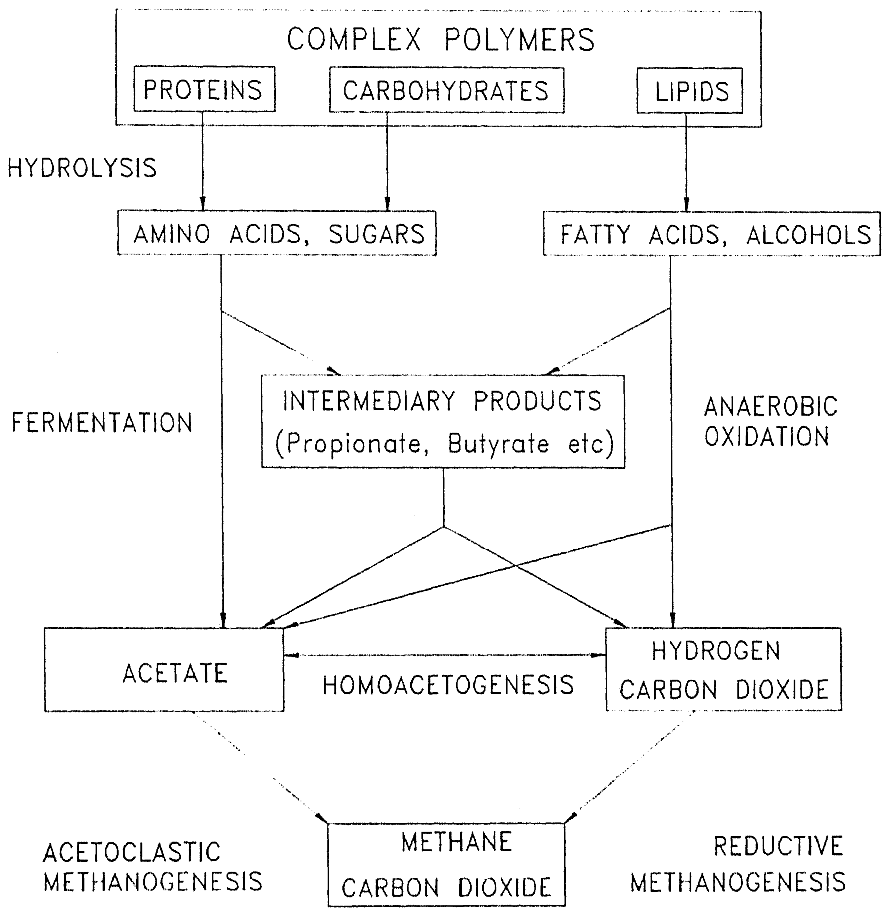


Fig. 2.2 Reaction Scheme for the Anaerobic Digestion of Polymeric Materials.(Adapted from Gujer and and Zehnder, 1983)

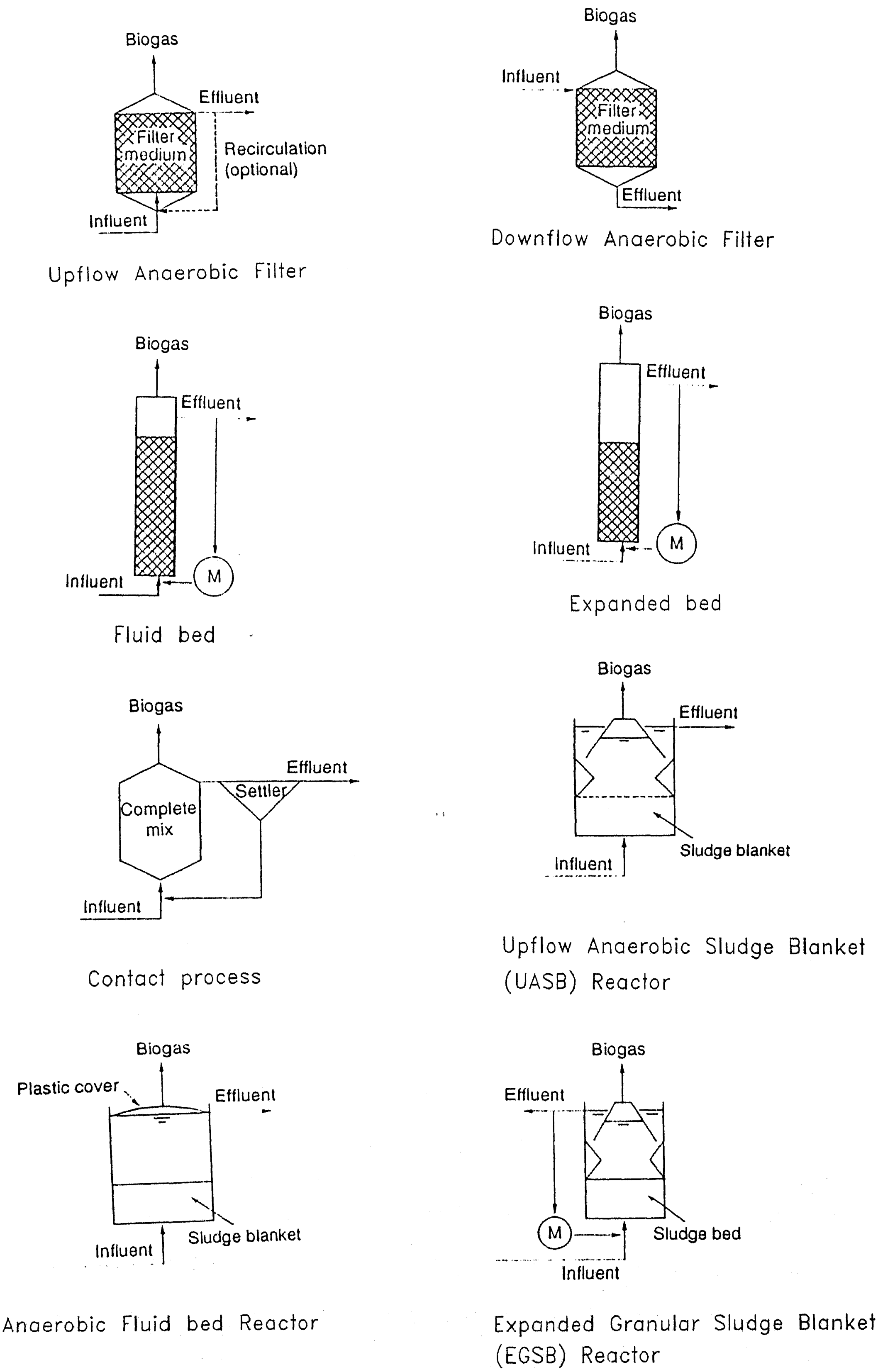


Fig. 2.3 Types of High Rate Reactors. (Lettinga and van Haandel, 1994)

2.2.2.2 The Upflow Anaerobic Sludge Blanket (UASB) Reactor

The UASB reactor was developed in the 1970s by Lettinga and his group members in the Netherlands (Lettinga and van Haandel, 1994). The UASB is the most widely used high rate anaerobic unit as it requires no attachment media for retention of biomass. The process relies on the tendency of anaerobic bacteria to form flocs or granules that are retained within the reactor by an efficient Gas Liquid Solid Separator (GLSS) located at the top of the reactor. High concentration of biomass in the reactor enables excellent COD removals of 80-95% at a short HRT ranging from 4 to 12 hours (Tilche and Vieira, 1991).

The cross section of a typical UASB is shown in Figure 2.4. Wastewater is introduced as uniformly as possible from the reactor bottom. It then, flows upwards through a blanket of anaerobic well settling sludge. The organic matter present in wastewater is degraded by microbes present in the blanket. As a result of anaerobic reaction that takes place in this blanket, methane and carbon dioxide are produced. These gases along with treated liquid and biomass rise up due to the hydraulic forces exerted by influent. The reaction zone is separated by the upper settling zone by GLSS. Two GLSS could be connected to each gas dome which collects the gas. To prevent the escape of biomass and gases beyond the GLSS, deflector beams are provided. The treated effluent flows through an aperture between the GLSS and deflector beam. The space between two GLSS surface acts as a settling zone. The inclined walls of GLSS provide increased area for liquid flow,

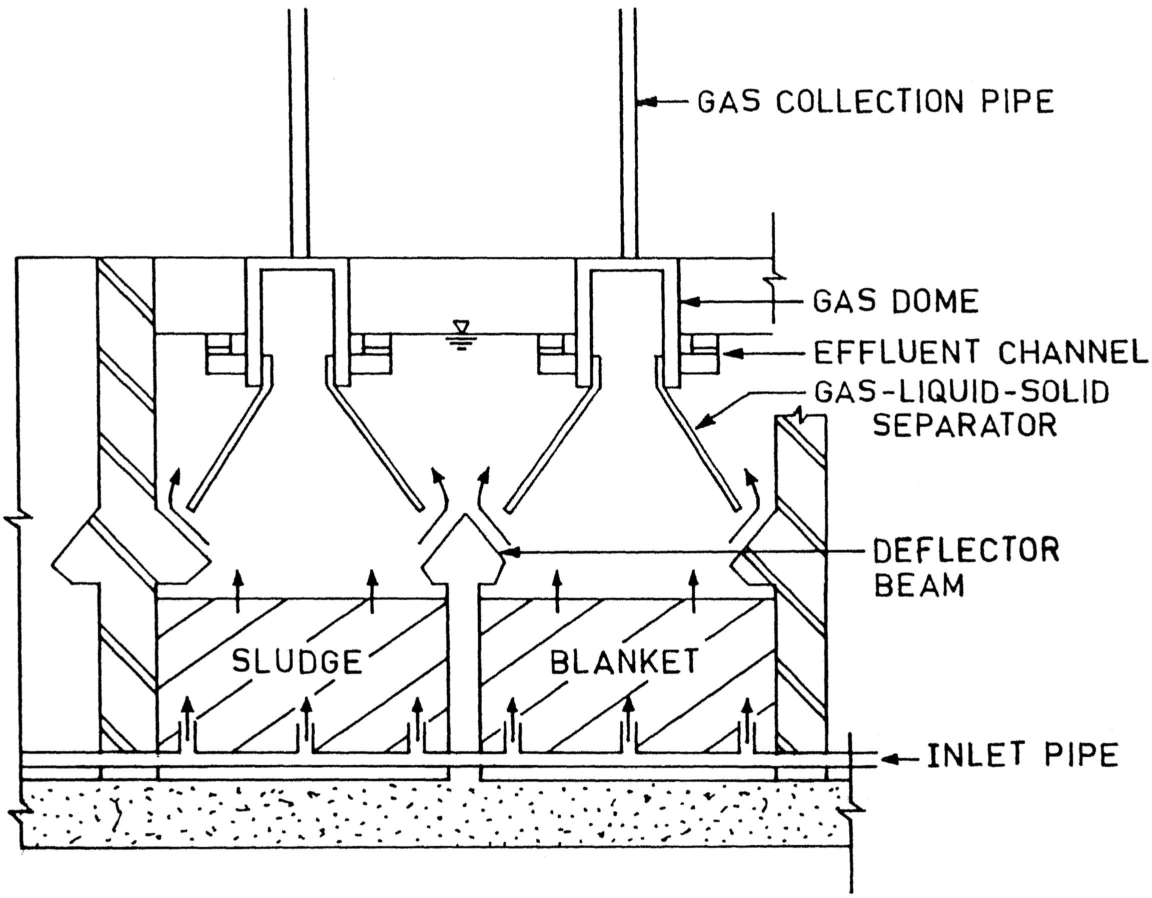


Fig. 2.4. Cross Section of a UASB Reactor.

so that settling velocity of liquid decreases as it rises. The biomass escaping with the effluent settles in settling zone and slides down the slope of the GLSS back into the reactor. Thus, the GLSS slope and the aperture velocity should be such that it does not hamper this process. Effluent from the settling zone is collected initially in gutters provided on both sides of the settling zone. These gutters empty the effluent into the main outlet channel.

2.3 Feasibility of UASB Process for Low Strength Domestic Wastewater

After the successful use of UASB process for high strength industrial wastes (distilleries, sugar, dairy etc.), its application in treatment of sewage under tropical climate conditions was studied by Lettinga *et al.* (1981). The deployment of anaerobic treatment for low strength organic load municipal wastewater (250-1000 mg COD/L) has to be considered with respect to the high threshold value of methane producing bacteria. Fukuzaki *et al.* (1990) showed that methanogens have a minimum concentration of substrate below which they do not function properly. This so-called threshold relates to undissociated acetic acid, the true substrate for acetoclastic methanogens. At pH 7.0, this threshold ranges from 130 mg/L total acetate for *Mthanosarcina* to 1-3 mg/L total acetate for optimal adapted *Methanothrix*. This could result in higher residual Volatile Fatty Acids (VFA) levels than that of incoming sewage and thus implicate low removal efficiency. This necessitates the need of highly adapted and well granulated sludges for the treatment of low strength domestic sewage (Mergaert *et al.* 1992).

In a UASB reactor, if the sludge granulation at the beginning state of the reactor is well developed, a very high organic loading can be applied. Sludge granulation is usually observed once the sludge loading rates exceed 0.6 kg COD/kg VSS.d (Hulshoff Pol, 1989). Severe washout of flocculent filamentous biomass occurs in UASB below this loading, which makes it difficult for development of granules, thus making UASB unsuitable for treatment of low strength domestic sewage, unless a pregranulated sludge on large scale is used.

The performance of pilot plants with municipal sewage is given in Table 2.1. Most of these reactors were inoculated with granulated sludge from UASB or digested activated sludge. The results presented in the table indicate that it is possible to treat domestic wastewater with UASB with a COD removal percentage ranging from 50 to 75.

The results of some of the full scale installations are given in Table 2.2. It can be observed that the performance of the plants is significant despite the ambient temperatures below 20°C. The influents fed to the UASB plants were of medium strength municipal wastewater.

The UASB plant with capacity of 5 MLD (column 4 of Table 2.2) was installed at Jajmau, Kanpur under the Indo-Dutch program in 1989, as a part of Ganga Action Plan (GAP). This was the first demonstration plant to treat domestic wastewater under Indian tropical climates. The maximum BOD removal reported was 77%. A oxidation pond with one day detention time was appended as a polishing unit before discharging the effluent into Ganga. The

Table 2.1 Performance of Treatment of Municipal Wastewater with Pilot Plant UASB Reactors

Volume (L)	T (°C)	HRT (h)	COD_{inf} (mg/L)	COD Removal (%)	Referance
120	12-16	24	688	55-75	Lettinga *et al.* (1983)
110	12-18	18	465	65	Monroy *et al.* (1988)
120	19-28	4	627	74	Barbosa and Sant' Anna (1989)
106	35	4	300	65	Vieira (1988)
160	20	6	1076	64	Mergaert (1990)

Table 2.2 Performance of Full Scale Anaerobic Reactors Treating Municipal Wastewater

	Netherlands Bergambacht (1)	U.S.A. Knoxville (2)	Colombia Bucaramanga (3)	India Kanpur (4)
Process design				
Reactor type	UASB	FFAB	UASB	UASB
Volume (m^3)	20	19	35	1200
HRT (h)	10	24	5	6
T (°C)	15-16	10-25	23-27	>20
Reduction				
BOD (%)	24-53	70	80	77
COD (%)	24-54	60	66	80
TSS (%)	43-64	60-70	70	85
Effluent Characteristic				
BOD (mg/L)	40-110	40	39	76
COD (mg/L)	170-303	100	145	200
TSS (mg/L)	43-80	53	70	128

UASB = Upflow anaerobic sludge blanket
FFAB = Fixed film anaerobic bioreactor
1. de Man and Lettinga (1987); 2. Genung *et al.* (1982); 3. Jakma *et al.* (1987); I.I.T. Kanpur Report (1995).

monitoring on the performance of UASB and post treatment based on composite sampling programme has indicated a BOD removal to the extent of 93% during winter months (I.I.T. Kanpur Report, 1995). The reduction of total coliforms (TC) and fecal coliforms (FC) by UASB was not satisfactory. However with the incorporation of oxidation pond in series, the removal of TC and FC was three log reduction. The nematodes removal ranged between 22 to 61% (Venkobachar, 1995). This makes the treated effluent suitable for disposal into Ganga.

A UASB reactor of 36 MLD capacity to treat 9 MLD of tannery effluent diluted with 27 MLD of domestic wastewater (DWW) was constructed and commissioned in March, 94 at Jajmau Kanpur as a part of Ganga Action Plan Phase-I. It was demonstrated that

active anaerobic sludge could be developed from DWW during the primary startup period of 150 days. The COD and BOD removal efficiencies were at 60 % during this primary startup period (Prasad, 1995).

Amongst the UASB plants listed above better performances are observed for plants operated above 20°C but required post treatment for disposal. As reported in Table 2.2, the relatively low strength municipal wastewater treatment in Knoxville, USA was carried out using Fixed Film Anaerobic Reactor (FFAB). Even the operational temperature was ranging from 10-25 °C.

The effluent BOD from UASB appears mainly contributed by the soluble substrate and the biomass escaping out of the reactor. This emphasize a need to modify the UASB reactor in order to meet the effluent standards. One such attempt was made by Joshi *et al.* (1988) based on findings of laboratory scale experiments with 'Anafil Digestor'. A plant of 0.4 MLD capacity was run for more than a year. This process treated raw degritted sewage, anaerobically at retention time of 12 h. The Anafil Digestor was a composite reactor. The influent flows initially downwards where rigid P.V.C. pipes are packed vertically, this provides adequate surface for development of biofilm. Then the flow passes over the sludge. The suspended solids get settled. The upward flow passes through another set of short length pipes and finally through an Anaerobic Filter (AF). In spite of detention of 12 h the average BOD_5 removal was only 77% whereas COD removal was 64%. The effluent BOD_5 and TSS exceeded the prescribed limits of disposal. This was attributed to the escape of biomass from the filter media

with the effluent.

2.4 Summary

A brief literature review indicates that anaerobic process of wastewater treatment has an edge over aerobic treatment methods. The suitability of UASB for medium to high strength domestic sewage, even in low temperature range of 12 to 20°C with HRT ranging from, 4 to 24 h is indicated in the literature. The UASB process can be applied to low strength domestic wastewater using granulated sludge. In order to meet the standards of disposal in terms of BOD_5 and TSS, the UASB reactor needs certain modifications, which if incorporated can meet the effluent standards for direct disposal.

3. SCOPE OF PRESENT WORK

The main objective of the present study was to compare the performance of an Upflow Anaerobic Sludge Blanket (UASB) reactor with that of a modified UASB reactor incorporating tube settlers in settler zone, treating low strength domestic wastewater inoculated with pregranulated biomass.

The study was aimed at achieving efficient treatment of domestic wastewater with minimum possible hydraulic retention time (HRT). The parameters defined for evaluation of the efficiencies were BOD_5, COD (total and soluble) and total suspended solids (TSS). The experimental study was undertaken in the following lines.

1. To evaluate the comparative performance of conventional and modified UASB reactors charged with pregranulated biomass to treat the dilute domestic wastewater at 6, 3, 2 and 1.5 h HRTs.
2. Determining the HRT at which both reactors fail to conform the effluent standards.
3. To investigate the biomass, liquid and gaseous phases of the reactors in terms of COD, BOD, TSS removals, VSS and specific methanogenic activity (SMA).
4. To study the settling characteristics of the biomass from reactors.

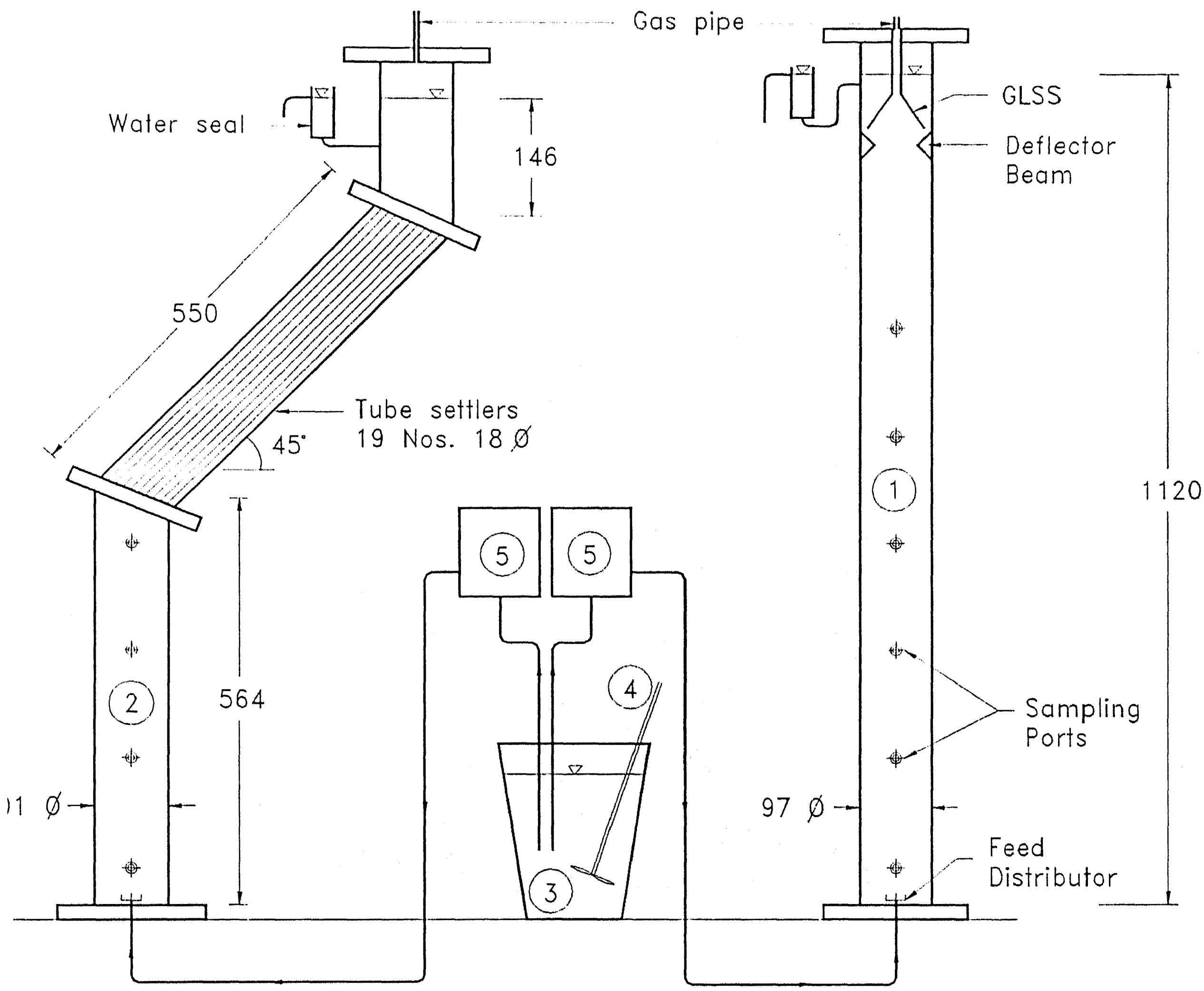
4. MATERIALS AND METHODS

In the present study a comparison of a laboratory scale Upflow Anaerobic Sludge Blanket (UASB) reactor and its modified version incorporating the tube settlers, to treat raw domestic wastewater was attempted. This chapter deals with the fabrication of conventional and modified reactors, characteristics of feed used and experimental methodology.

4.1 Materials

4.1.1 Upflow Anaerobic Sludge Blanket (UASB) Reactor

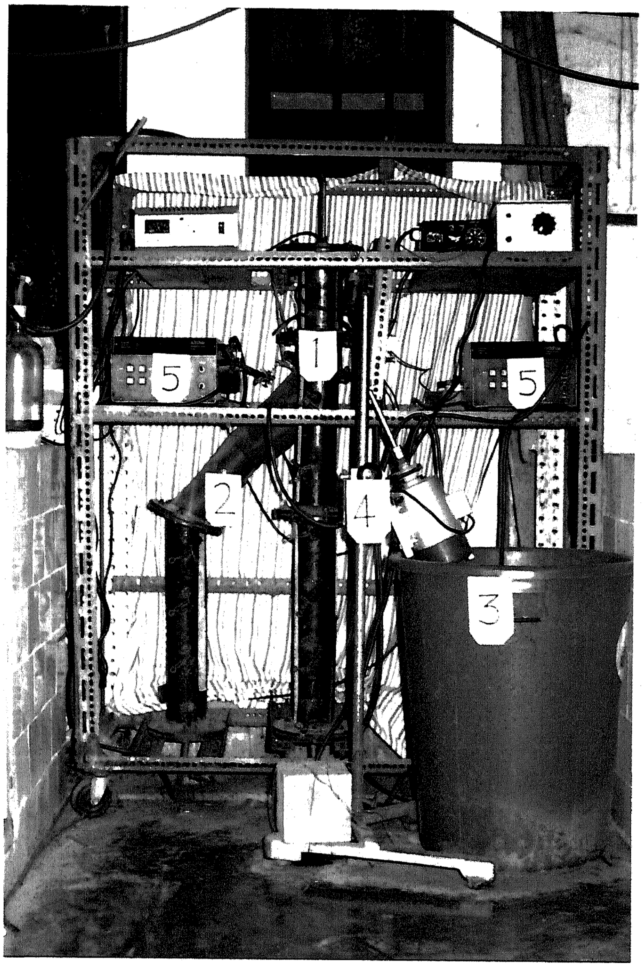
A laboratory scale Upflow Anaerobic Sludge Blanket Reactor (UASB) having a volume of 8.3 L and a height of 1120 mm, was fabricated and the schematic diagram is presented in Figure 4.1. The photograph showing both conventional and modified UASB is presented in Figure 4.2. The average internal diameter of the reactor was 97 mm. The reactor was built using molded acrylic sheets, so as to visually inspect the movement of sludge bed. A feed distributor made of glass was provided at the bottom of the reactor for proper distribution of sewage. Internal diameters for these inlets were 2 - 3 mm. Sampling ports for sludge spaced at 150 mm c/c were provided along the height of the reactor. The Gas Liquid Solid Separator (GLSS) comprised of a deflector beam and a conical settler having vertex angle of 55°, both were made of acrylic sheets. A water seal for effluent was provided to ensure anaerobic conditions at the top of the reactor. The gas produced was measured by liquid (saturated NaCl solution acidified with HCl) displacement.



1 UASB Reactor
2 Modified UASB Reactor
3 Sewage Holding Tank
4 Stirrer
5 Peristaltic Pump

All Dimensions in mm

. 4.1 Schematic Diagram of experimental setup showing the UASB and the Modified UASB reactors.



1 UASB Reactor
2 Modified UASB Reactor
3 Sewage Holding Tank
4 Stirrer
5 Peristaltic Pump

Fig. 4.2 Photographic view of experimental setup showing the UASB and the Modified UASB reactors.

4.1.2 Modified UASB Reactor

The modified UASB reactor used was the one designed, fabricated and operated by Grasius (1995) for the investigation on the performance of modified UASB reactors for treatment of several types wastewaters like highly soluble, colloidal and domestic sewage. The details of the reactor are shown in Figures 4.1 and 4.2. This had a volume of 9.10 L with over all height of 1115 mm. The average internal diameter was 101 mm. This reactor was composed of 564 mm of straight cylindrical portion over which an inclined portion at an angle of 45° containing 19 Nos. of 18 mm diameter tubes were placed. These tubes were made of PVC having length of 550 mm. The top portion of the reactor was a 146 mm straight cylinder with average internal diameter of 101 mm. This reactor was also built with acrylic sheets. One important feature of this reactor was absence of separate conventional GLSS. The provision of tube settlers was made to improve the retention of biomass in the reactor as well as to act as GLSS.

4.1.3 Influent and Feeding System

The feed to the UASB reactors was domestic wastewater from the campus of Indian Institute of Technology, Kanpur. Wastewater from sump well No. 2 was chosen for the experimental work as this served predominantly the residential area of the campus. As there was no significant difference in the BOD values of sewage throughout the day, the time selected for daily collection of sewage was 17:00 h. The average wastewater characteristics during the experimental study is given in Table 4.1.

Table 4.1 Characteristics of Sewage Fed to the Reactors

Parameters	Average*	Maximum	Minimum
¹COD_T, mg/L	172	262	92
²COD_S, mg/L	77	115	48
BOD_5, mg/L	41	56	33
TSS, mg/L	165	273	56
NH_3-N, mg/L	17	25	14
SO_4^{2-}, mg/L	60	66	58
pH	8.00	8.20	7.70
Alkalinity $CaCO_3$/L	428	468	410

* Average over the study period of 131 days.
1 COD_T = Total COD; 2 COD_s = Soluble COD

To facilitate easy pumping of sewage into the reactors, large suspended solids were removed by filtering the sewage through approximately 1.5 mm size strainer. It was then stored in a 110 L capacity holding tank. The average sewage retention time in holding tank was 10-12 hours. The sewage from the holding tank was pumped into the reactors using two peristaltic pumps (PP20, Micllins, Madras). Flexible rubber tube was used for influent pumping. No external control was exercised on pH and temperature of reactors and sewage in holding tank.

4.1.4 Biomass

The biomass used in the study was developed in the modified UASB reactors by Grasius (1995) during his research work. This biomass was well granulated. The maximum granule size was

approximately 4 mm. The main characteristics of biomass used in this study are given Table 4.2.

Table 4.2 Characteristics of Biomass

Parameters	Value
Total Suspended Solids (TSS), g/L	57.94
Volatile Suspended Solids (VSS), g/L	14.54
VSS/TSS	0.251
Sludge Volume Index (SVI), mL/g TSS	14
Specific Methanogenic Activity (SMA), g COD/g VSS.d	0.065

4.2 Methods

4.2.1 Studies on Solid (biomass) Phase of UASB Reactors

Retained sludge is the most important component of the UASB reactor. In order to evaluate the variation of biomass content in the reactor, sludge samples at different heights were collected from the sludge collection ports. The samples were analysed for TSS, VSS and Specific Methanogenic Activity (SMA). The TSS and VSS were determined every 15 days. The sludge profiles in terms of soluble COD, total alkalinity, pH and SMA were also determined at every hydraulic retention time after the steady state were attained.

4.2.2 Studies on the Liquid Phase of UASB Reactors

To evaluate the efficiencies of the reactors, the influent and effluent samples were collected and analysed for total COD, Soluble COD, BOD and TSS. Influent from the sewage

holding tank and the effluent samples from the top exit of the reactor, after passing through the water seal were composited from grab samples collected over a period of 24 h. Samples were stored at 4°C prior to analysis.

4.2.3 Studies on Gaseous Phase of UASB Reactors

In order to evaluate the composition of the gas generated in the reactors, gas samples were collected in syringe from the rubber tube connecting the reactor and the bottle containing salt solution. Gas composition was determined using a chromatograph (NUCON-5700, India) using Carbosphere column.

4.2.4 Analytical Techniques

4.2.4.1 BOD and COD

Influent and effluent samples collected from both the reactors were centrifuged at 6000g for 15 min using a centrifuge (Remi, R-24, India). Both centrifuged and uncentrifuged samples were analysed for COD using closed reflux method BOD was determined only for uncentrifuged samples, as described in Standard Methods (1989).

4.2.4.2 Volatile Fatty Acids (VFA) and Total Alkalinity (TA)

Direct titration method described by Delallo and Albertson (1961) was used to determine the VFA and TA. This involves titration of the samples with strong acid to pH 4.3 which gives alkalinity due to bicarbonate, VFA and phosphates. When the sample pH is reduced to 3.3, bicarbonate ions will be converted to carbonic acid and subsequent boiling of the sample removes all of the carbonic acid as carbon dioxide. The back titration from pH 4 to 7 measures the alkalinity due to organic acids. The conversion

factor for determination of VFA from volatile acids alkalinity depends on the proportion of acid which is titrated between pH 4 to 7.

A 25 mL of centrifuged sample was titrated to a pH of 4.3 with 0.1 N sulphuric acid. The volume of acid used was noted and titrated was continued to pH of 3.5-3.3. The sample was gently boiled for three minutes and cooled in a water bath to room temperature. It was then titrated against 0.05 N NaOH upto pH 4. After noting the burette reading, the titration was continued to pH 7 and final reading was noted. VFA concentration was calculated as follows :

VFA Alkalinity, mg/L as $CaCO_3$ = mL 0.05 N NaOH x 2500/mL sample

VFA, mg/L as CH_3COOH = VFA Alkalinity x 1.5

Total Alkalinity, mg/L as $CaCO_3$ =

$$\frac{\text{mL } 0.1\text{N } H_2SO_4 \text{ (used upto 4.3) } \times 5000}{\text{Volume of sample (mL)}}$$

4.2.4.3 TSS and VSS

The determination of TSS and VSS was done as per the Standard Methods (1989).

4.2.4.4 Sulphates

The sulpates present in the influent and effluent samples from the two reactors were determined by turbidimetry as per Standard Methods (1989).

4.2.4.5 Ammonia Nitrogen

Ammonia Nitrogen present in the influent and effluent samples from the two reactors were determined by Nesslerization Method as per Standard Methods (1989).

4.2.4.6 Specific Methanogenic Activity (SMA)

The specific rate of acetoclastic methanogenesis of the sludge can be evaluated by a simple test devised by Valcke and Verstraete (1983). This test is based on the findings that during a maximum incubation period of 24 h, biomass growth is minimal and acetate conversion rate obeys zero order kinetics and are not affected by substrate concentrations between certain limits (Lawrence, 1969).

The sludge sample was first diluted to get a VSS concentration of approximately 5 g/L with a mineral solution of composition as given in Table 4.3.

Table 4.3 Composition of Mineral Solution* for Determination of SMA

Compound	Concentration, mg/L
KH_2PO_4	2500
K_2HPO_4	1000
NH_4Cl	1000
$MgCl_2$	100
Yeast extract	200
$Na_2S.7H_2O$	100

* Valcke and Verstraete (1983)

To a series of 500 mL flasks, 350 mL each of this diluted sludge was added. The samples were subsequently acclimated to 24 - 48 h at 30°C without the addition of substrate. Thereafter, increasing amounts of sodium acetate as substrate was added to get sludge loading in the range of 0.3 to 1.0 g acetate/g VSS. Care

was taken to introduce as little oxygen as possible into the liquor. The pH of sludge samples was adjusted to 6.7 either with 1N HCl or 1N NaOH. Then the flasks were flushed with nitrogen gas for at least 1 minute and incubated at 30°C for 24 h in a water bath shaker (Narang Scientific Works, India). The gas produced was bubbled through 1N NaOH solution to remove CO_2 and the volume of CH_4 produced was measured by liquid displacement. Gas measurements were noted upto 24-30 h, after which the VSS content of the sludge sample were determined. The maximum specific methane production rate was calculated and reported as mL CH_4/g VSS.d. If the maximum CH_4 production had occured at the highest sludge loads than 1.0 g acetate/g VSS were employed.

5. RESULTS AND DISCUSSION

The main objective of the present study was to compare the performance of an Upflow Anaerobic Sludge Blanket (UASB) reactor with that of a modified UASB reactor consisting of tube settlers in place of GLSS treating raw dilute domestic wastewater. The experimental study consisted of a number of steady-state continuous flow runs with hydraulic retention times (HRT) ranging from 6 to 1.5 h. The experimental results with the pertinent discussion are presented in the following sections.

5.1 Start-up of the Reactors

The reactors were started by charging them with pregranulated biomass of 3.25 litres having a volatile suspended solids (VSS) of 47.3 grams. Use of pregranulated sludge is expected to curtail the primary start-up period of the reactor.

5.2 Performance Evaluation of the Reactors

Liquid, solid (biomass) and gaseous phases of the reactors were subjected to investigations. After attainment of steady state, the average results over a time period were used to evaluate the performance of the reactors. In this section the results on the following aspects are presented with pertinent discussion.

a. Comparative performance of conventional and Modified UASB reactors operating at HRTs of 6, 3 and 2 h.

b. Performance evaluation of Modified UASB reactor with HRT of 1.5 h.

The reactors were monitered on alternate days for total and

soluble COD, TSS, TA and VFA, while pH was determined daily. The reactors were maintained at ambient temperatures, which were recorded daily. The BOD_5 was determined several times after reactors had attained the steady state and the average values are reported.

Reactors performance was assessed on the basis of COD, BOD_5 and TSS removals. In case of COD, the removal were expressed in two ways based on i) total influent and effulent, and ii) soluble influent and effulent COD. The first represents the overall removal, comprising the soluble and the suspended material, thus reflecting the organic matter removal by physical action and biological decomposition. The second expresses the soluble organic substances removal, predominantly representative of the biological action. The startup of both the reactors began on the 18th Oct, 95 using raw domestic wastewater whose characteristics are presented in Table 4.1.

5.2.1 Performance of Reactors at the HRT of 6 h

The UASB and modified UASB reactors containing pregranulated biomass were fed with raw domestic wastewater for 68 days and their performance is presented in Figure 5.1. A remarkable increase in the total and soluble COD and TSS removals were observed after the day 30, following which a steady-state was observed. This indicates that it is possible to employ pregranulated sludge for decomposition of organic matter. Table 5.1 gives the steady-state experimental results concerning the reactor influent and effulent values.

The temperature at 6 h steady-state run had ranged from 18

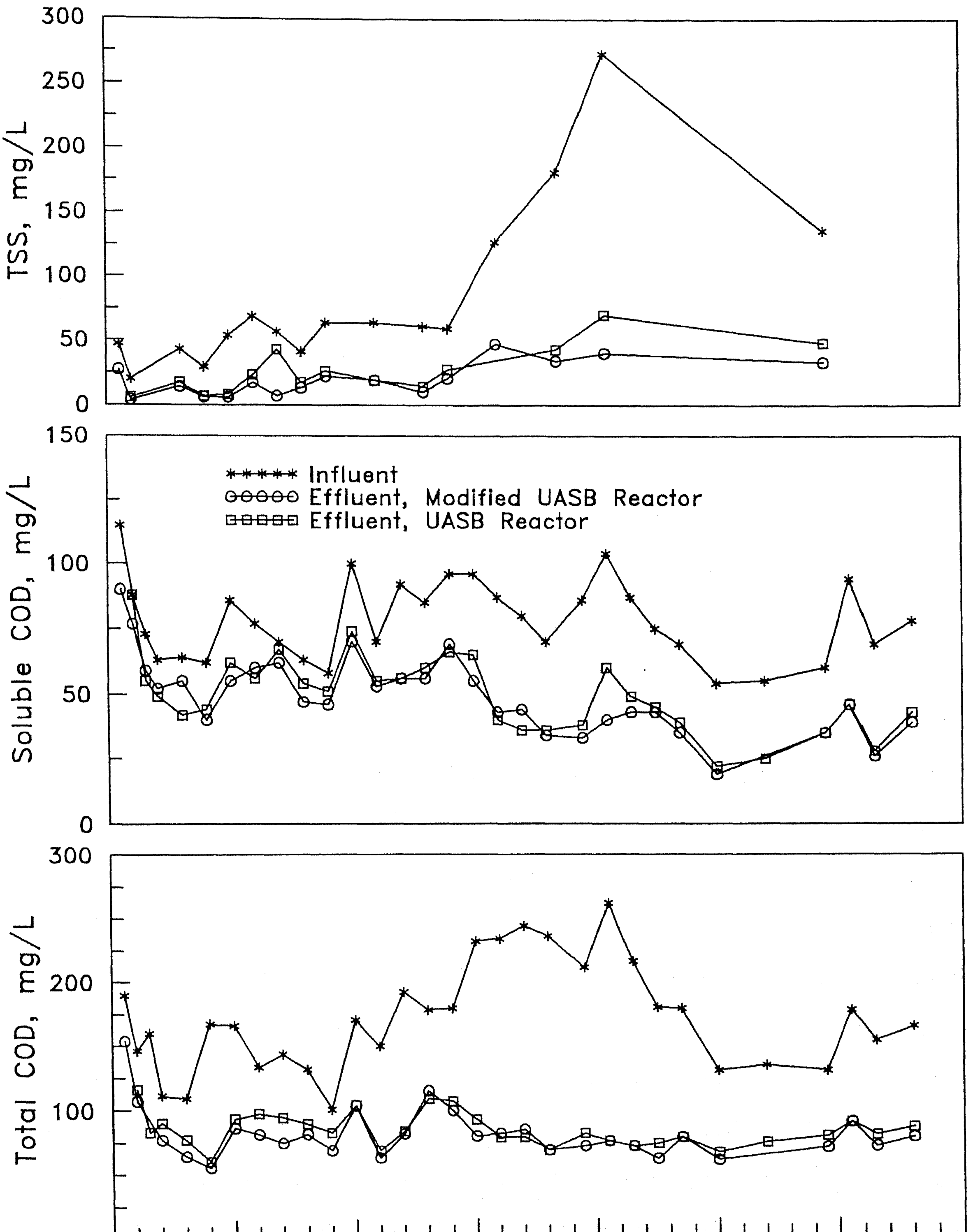


Fig. 5.1 Performance of Reactors with HRT of 6 h

Table 5.1 Performance of Reactors with HRT of 6 h

Parameters, mg/L	Influent	Effluent	
		UASB	Modified UASB
Total COD	192	79 (58.85)	74 (61.45)
Soluble COD	76	39 (48.68)	37 (51.32)
BOD_5	46	11 (76.08)	11 (76.08)
TSS	170	54 (68.23)	38 (77.65)

Values in parenthesis indicate percent removal

to 23°C. A daily variation of 1 to 1.5°C was observed, as no temperature control excercised. The influent pH was ranging from 7.80 to 8.15. The average effluent pH for UASB reactor was found to be 0.05 to 0.1 units less than the influent pH, where as it was 0.1 to 0.2 units less for modified UASB reactor.

Table 5.1 shows that the BOD_5 and TSS values were well below the prescribed limits of 30 and 50 mg/L respectively for the modified reactor. The TSS value in UASB reactor was just above 50 mg/L. Although the BOD_5 removals were identical for both the reactors, the modified reactor was more efficient to trap the TSS than the conventional UASB. The tube settlers in modified reactor in place of GLSS appear to be more efficient in trapping the suspended solids. Similar explanation is also valid for marginally higher total COD removals by modified UASB.

It may be possible to reduce the HRT for both the reactors and in the next section the performance of the reactors at a HRT of 3 h is presented.

5.2.2 Performance of Reactors at the HRT of 3 h

The HRT for both UASB and modified UASB reactors were reduced to 3 h on 28th Dec, 95. After the 10th day, a fairly constant percent removal in total COD was observed. The reactor was operated for 10 more days after it has attained steady-state. Figure 5.2 shows the performance of the reactors at 3 h HRT. Table 5.2 gives the average influent and effulent characteristics at steady-state. The temperature at 3 h HRT was ranging from 18 to 20°C. The influent pH was ranging from 7.90 to 8.10. The average effluent pH for UASB reactor was found to be 0.05 to 0.1 units less than the influent pH, where as it was 0.1 to 0.2 units less for modified UASB reactor.

Table 5.2 Performance of Reactors with HRT of 3 h

Parameters, mg/L	Influent	Effluent	
		UASB	Modified UASB
Total COD	186	96 (48.38)	87 (53.23)
Soluble COD	76	53 (30.26)	51 (32.89)
BOD_5	39	23 (41.02)	20 (48.72)
TSS	144	48 (66.67)	38 (73.61)

Values in parenthesis indicate percent removal

The results presented in the above Table indicate that the modified UASB was able to meet the effluent standards better than UASB. It was, thus, appropriate to reduce the HRT further so that the cost of reactor can be decreased. Another problem encountered with UASB was the occasional lifting of the sludge bed while this was not observed in modified UASB.

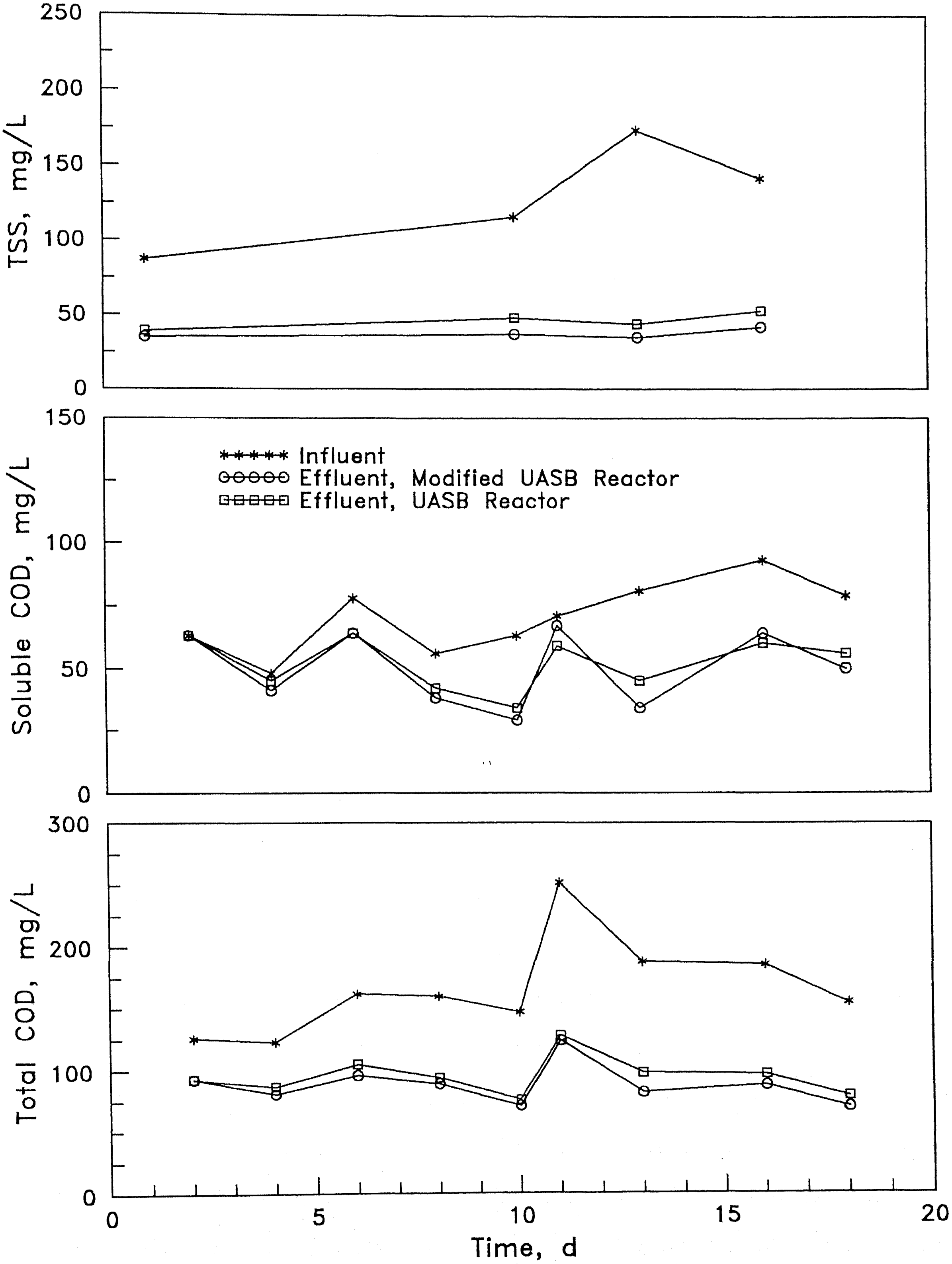


Fig. 5.2 Performance of Reactors with HRT of 3 h

5.2.2 Performance of Reactors at the HRT of 2 h

After 20 days of run with HRT of 3 h, both the reactors were switched-over to 2 h HRT in order to increase the organic loading rate. This run was started on 17th Jan, 96. After the 10th day, fairly uniform total COD removals were observed. Figure 5.3 shows the performance of the reactors with HRT of 2 h. At this retention time, the sludge bed in both reactors was expanded more than that at HRT of 3 h. In the UASB reactor, a part of the sludge blanket (approximately one third of its depth) was lifted upto the deflector beam. This was obviously due to the increase in rise velocity as a result of increased influent flow rate. Further the sludge was ladden with gas bubbles. Roding of sludge blanket was employed to remove the entrapped gas bubbles. After this, the biomass was allowed to settle down by stopping the flow to the reactor for a short time. This problem was encountered every day which required roding.

The roding of sludge was discontinued after 19 days to assess the extent of possible biomass washout from the UASB reactor. Once roding had ceased, the biomass that was lifted, escaped from the UASB reactor. However, a part of the biomass lifted remained entrapped in the GLSS. No such problem was encountered in modified UASB reactor. Both the reactors were run for further 21 days. The average results are presented in Table 5.3.

It is evident from the results that the performance of modified UASB is marginally better than UASB in terms of COD and BOD removal but significantly better as far as TSS removal is concerned. BOD_5 removals were observed to be higher than soluble

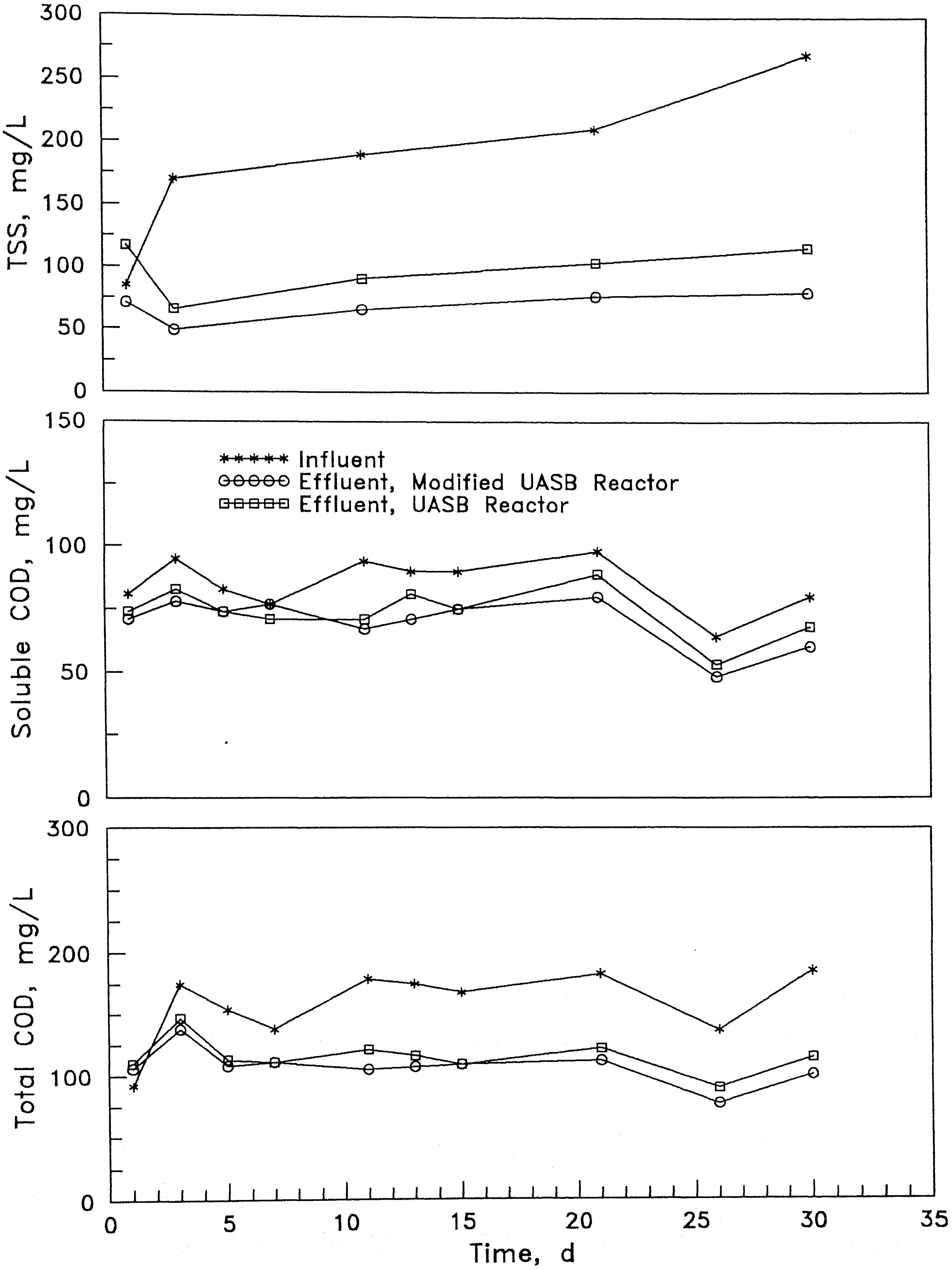


Fig. 5.3 Performance of Reactors with HRT of 2 h

Table 5.3 Performance of Reactors with HRT of 2 h

Parameters, mg/L	Influent	Effluent	
		UASB	Modified UASB
Total COD	167	111 (33.53)	102 (38.92)
Soluble COD	86	73 (15.12)	67 (22.09)
BOD_5	41	28 (31.70)	26 (36.58)
TSS	210	94 (55.23)	68 (67.62)

Values in parenthesis indicate percent removal

COD removals for all HRTs. As per Noyola *et al.* (1988), the escape of soluble COD could be significant for low strength wastewaters. Both reactors, however, have satisfied the effluent BOD standards. The TSS from modified UASB was slightly higher than the standard value while that for UASB was much higher.

The temperature had ranged from 16 to 20°C. The influent pH had changed from 7.7 to 8.15. The average effluent pH for UASB reactor was found to be 0.05 to 0.10 units less than the influent pH, where as it was 0.1 to 0.2 units less for modified UASB reactor.

5.2.4 Performance of Modified UASB Reactor at the HRT OF 1.5 h

The study with HRT of 2 h demonstrated that the conventional UASB had failed as washout of considerable biomass had occured due to high rise velocity. Hence, the operation of this reactor was discontinued. The modified UASB, however was operated at a HRT of 1.5 h from 17th Feb, 96. The removal rates were fairly constant from the 2nd day of operation. Figure 5.4 shows the performance of modified UASB reactor for 12 day run.

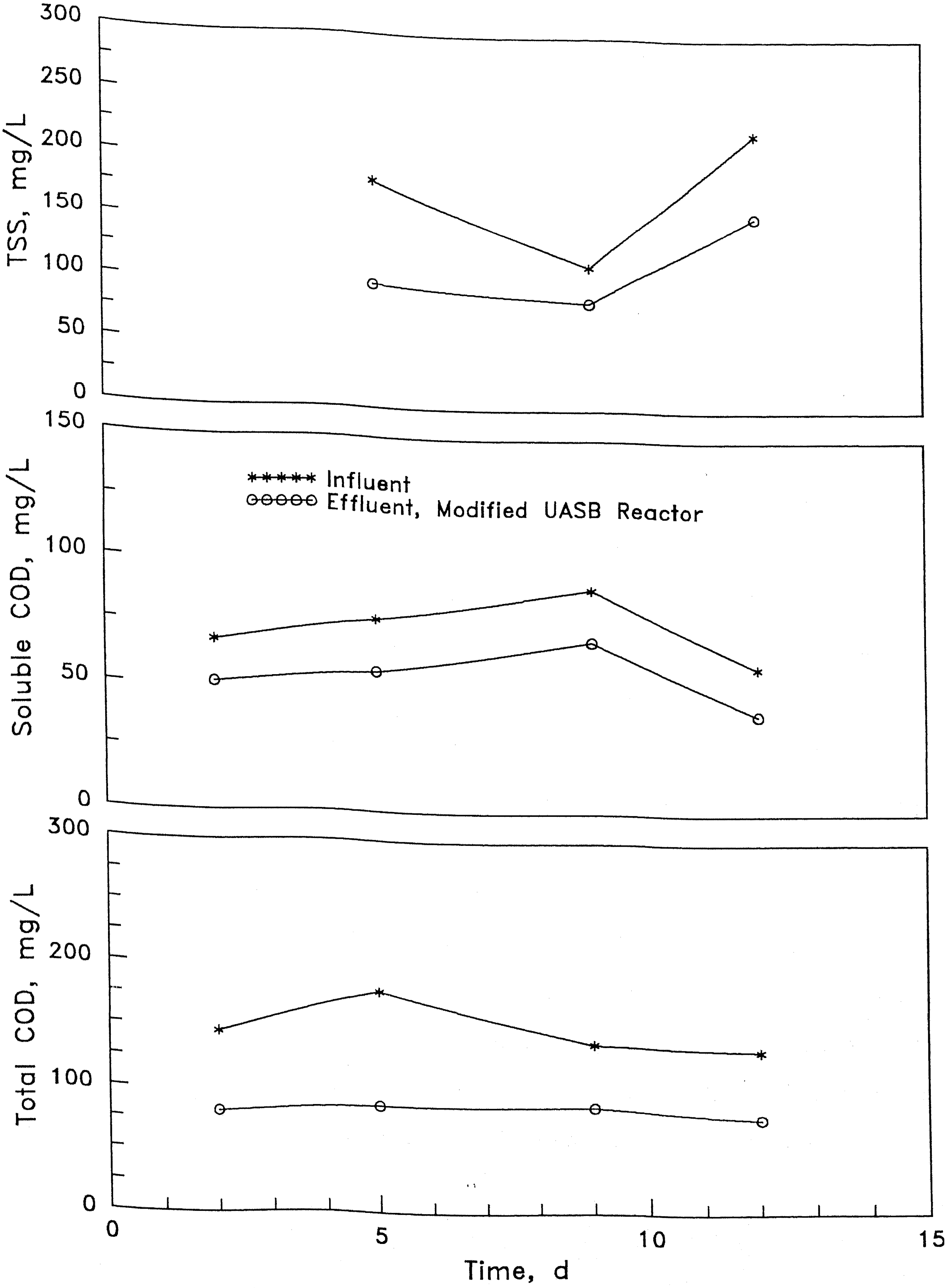


Fig. 5.4 Performance of Modified UASB Reactor with HRT of 1.5 h

Table 5.4 give average values of various parameters.

Table 5.4 Performance of Modified UASB reactor with HRT of 1.5 h

Parameters mg/L	Influent	Effluent from Modified UASB
Total COD	148	81 (45.27)
Soluble COD	68	49 (27.94)
BOD_5	40	26 (35.00)
TSS	174	114 (34.48)

Values in parenthesis indicate percent removal

The results indicated that though the effluent BOD was within the prescribed limits, the TSS has exceeded the limits. However, the higher value of effluent TSS (114 mg/L) could be due to escape of smaller and lighter flocculent puffy material along with the effluent. Once such materials are removed from the reactor by prolonged operation, it may meet the TSS standards also.

The temperature was ranging from 20 to 22^{o}C. The influent pH was ranging from 7.70 to 8.0. The average effluent pH was found to be 0.1 to 0.2 units less than the influent pH.

During operation of the modified UASB at the HRT of 1.5 h, the sludge bed was completely fluidised and sludge entered into the tube settler zone of the reactor. Washout of this biomass along with the effluent as in UASB at 2 h HRT did not occur indicating efficient capture of biomass in the settlers.

5.3 Investigations on Three Phases of the Reactors

Investigations on three phases of the reactors namely biomass, liquid and gas were carried out to understand the phenomenon of organic matter removal, capture of suspended solids, waste stabilisation and product formation.

5.3.1 Investigation on Biomass and Liquid phases

The biomass present in the sludge blanket is responsible for decomposition of organic matter with the production of CH_4, CO_2, H_2S etc. Along the height of sludge blanket, waste stabilisation and product formation occur. The waste stabilisation is determined in terms of COD and VFA profiles. The diagnostic parameter of biomass namely specific methanogenic activity was determined corresponding to each HRT. VSS, TSS and alkalinity profiles were determined along with the height of sludge blanket.

5.3.1.1 COD Profile

The COD profile for both the reactors operating at 6 h HRT, is shown in Figure 5.5. A high soluble COD value at the bottom port can be observed for both the reactors. This is attributed to the hydrolysis of suspended solids to VFA. This high soluble COD gradually decreased along the height of sludge blanket as methanogenic activity increased. After about 350 mm of sludge blanket height there was no change in COD values. Soluble COD profile in Figure 5.6 for the HRT of 3 h shows a similar trend as 6 h HRT, except in case of UASB reactor. In this the soluble COD increased in the lower part of sludge blanket followed by its utilisation. This could be due to the removal of

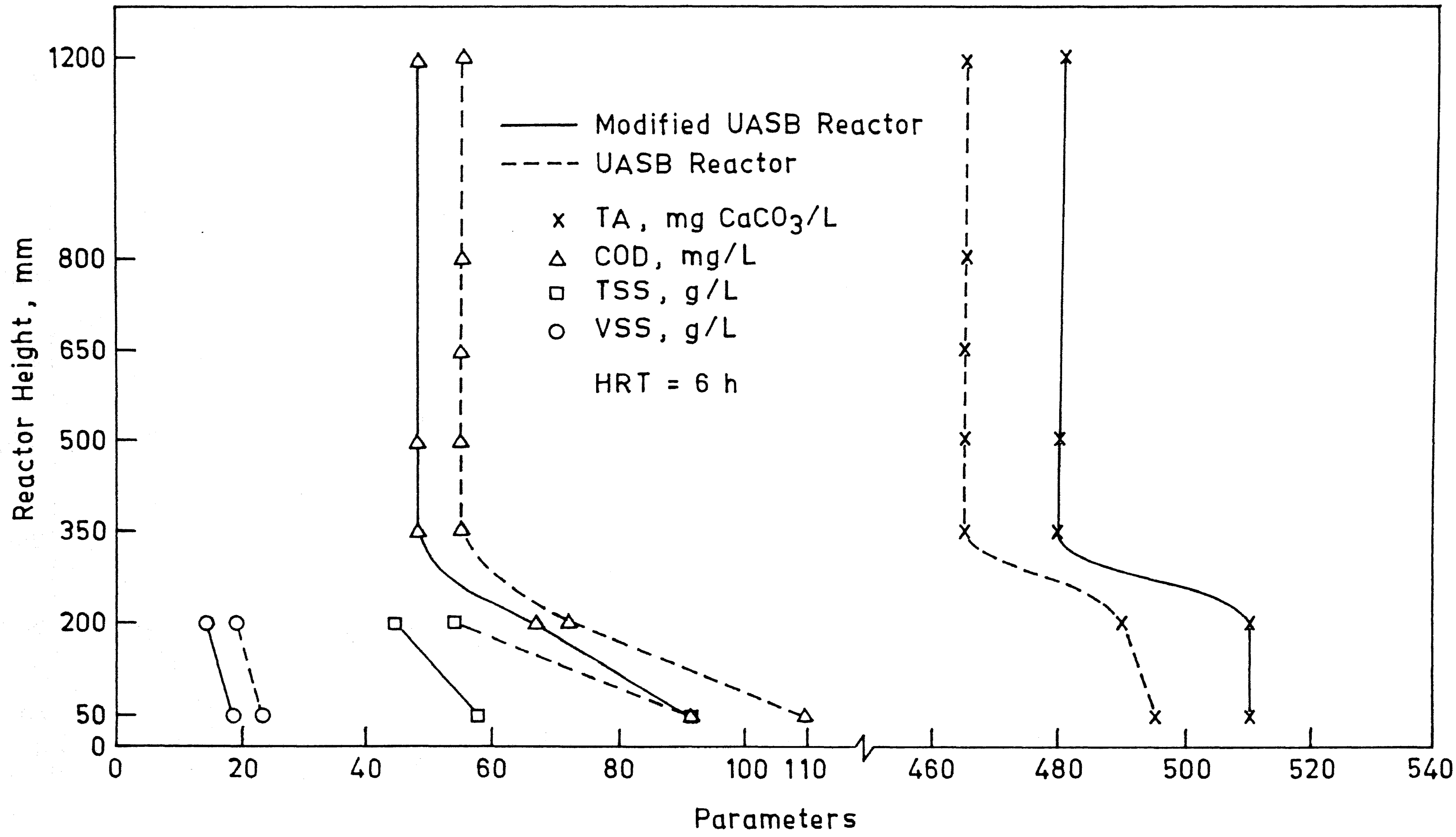


Fig. 5.5. Profile of Various Parameters Along the Reactor Height with HRT of 6h.

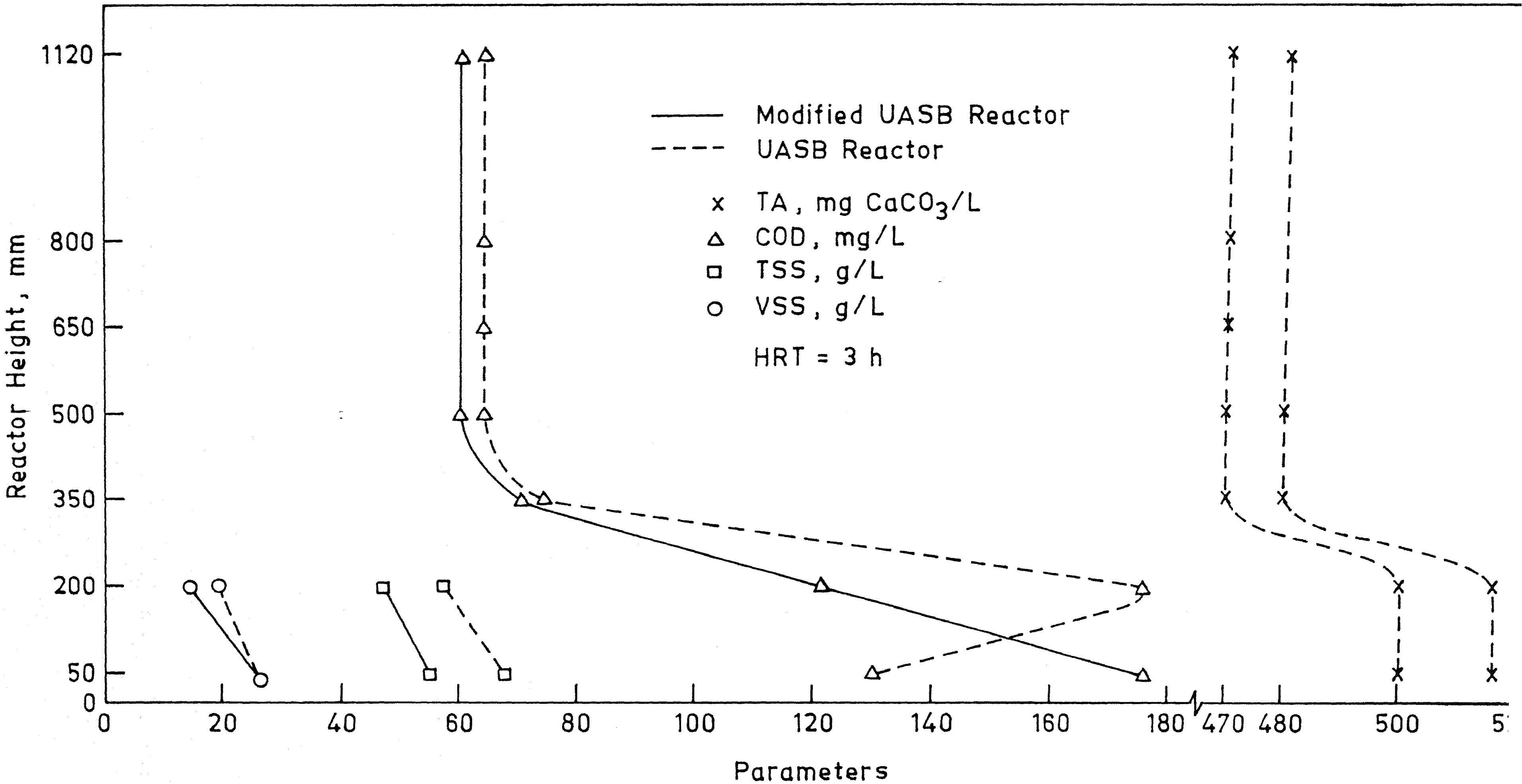


Fig. 5.6. Profile of Various Parameters Along the Reactor Height with HRT of 3 h.

soluble COD in the top portion of sludge blanket where methanogens appear to be more active.

The COD profile with HRT of 2 h in Figure 5.7 shows expansion of sludge bed in both the reactors and exhibits two peaks of soluble COD.

5.3.1.2 Total Alkalinity (TA)

The TA as per Figures 5.5 to 5.7 was high in the bottom sludge bed and there was a gradual reduction in the value upto a blanket height of 350 mm for 6 and 3 h HRTs and upto 500 mm for 2 h HRT for both reactors. After these heights, the value of TA remained fairly constant. This initial increase could be due to the addition of anions of volatile fatty acids to the influent TA. Further, the effluent TA for both the reactors were higher than the influent TA values which may be due to dissolution of CO_2 produced during anaerobic degradation with the formation of HCO_3^- and $CO_3^=$.

5.3.1.3 Volatile Fatty Acids (VFA)

The VFA concentration in the effluents of both the reactors were ranging from 25 - 40 mg/L as acetic acid. The relatively low values of VFA coupled with pH and alkalinity of feed domestic wastewater is not expected to cause substrate inhibition to methanogens.

5.3.1.4 VSS and TSS

Relatively higher values of VSS and TSS were found in the lower portion of the reactor which indicates more biomass in the lower portions as per Figures 5.5 to 5.7. During the run with HRT of 2 h, a higher expansion in the sludge bed, due

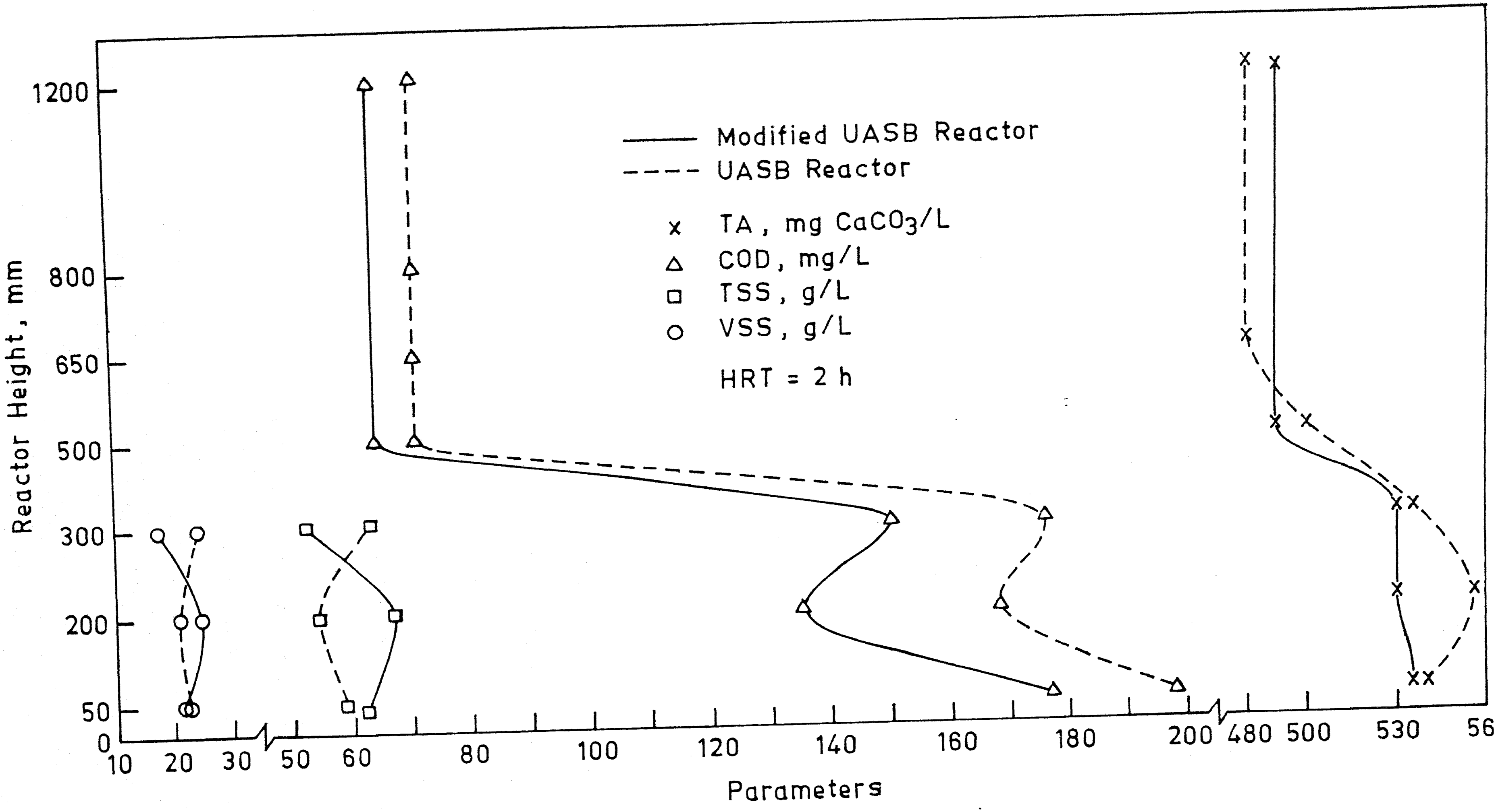


Fig. 5.7. Profile of Various Parameters Alog the Reactor Height with HRT at 2h.

to increased rise velocity, was observed for both the reactors. The UASB reactor showed the higher TSS and VSS concentrations in the top (350 mm) portion of the sludge blanket, whereas the modified UASB reactor showed the higher TSS and VSS concentrations in the middle of sludge bed (200 mm).

5.3.1.5 Specific Methanogenic Activity (SMA)

The SMA was determined for the samples collected from the sludge withdrawal ports for both the reactors. The SMA values for samples collected from different ports were nearly same. Hence average SMA values for the reactors for different HRT were calculated and Figure 5.8 depicts the SMA as a function of HRT, for the entire study period. A significant rise in the SMA can be seen with decrease in HRT. The SMA values for sludge from modified UASB reactor were slightly higher than that from the UASB reactor. This shows better retention of slow growing methanogens in the modified UASB reactor. The maximum SMA value for modified UASB reactor was found to be 0.207 g COD/g VSS.d as against a high value of 0.19 g COD/g VSS.d for UASB reactor. These values are comparable with the results obtained by Lettinga *et al.* (1981), Grin *et al.* (1983), Schellinkhout *et al.* (1985) and Barbosa and Sant' Anna (1989) which are reported in the range of 0.1 - 0.25 g COD/g VSS.d with domestic wastewater as feed.

5.3.1.6 Settling Characteristics of Biomass

The settling properties of granular biomass which is so important for the sludge bed can be assessed by determining the Sludge Volume Index (SVI). The SVI values for

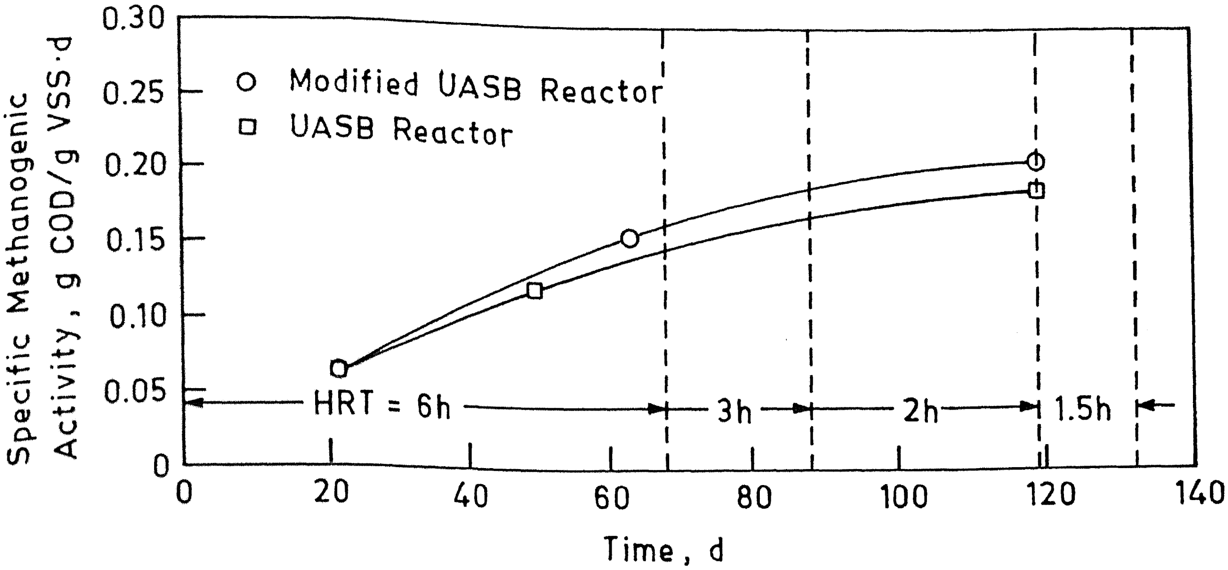


Fig. 5.8. Variation of Specific Methanogenic Activity with Time.

granular sludge, are in the range of 12-20 mL/g (Hulshoff Pol, 1989). The SVI values for both UASB and modified UASB sludge were determined to be 14 mL/g. An appropriate alternative to SVI appears to be settling velocity of the biomass granules. The use of settling velocity to characterise the sludge granules was employed by Hulshoff Pol (1989). A settling column of 36 mm diameter with a height of 1.85 m was used to determine the settling velocities of granular biomass present in the reactors.

The settling velocity as a function of weight fraction is presented in Figure 5.9. The plot shows the maximum settling velocity of 150 m/h for granules from modified UASB reactor at 1.5 h HRT and a value of 135 m/h for UASB reactor operating at 2 h HRT. About 65% of biomass had settling velocity between 10-30 m/h for both the reactors. Settling velocities of 20 to 80 m/h are reported for granules depending on granule size and density (Hulshoff Pol, 1989). As per the results, the biomass in UASB reactor had a higher percentage of granules with a higher settling velocity than modified UASB. This was mainly because the settling test was conducted on sludge from UASB after the sludge wash out had occured during which the smaller fractions of biomass might have escaped from the reactor.

5.3.2 Investigations on Gaseous Phase.

The total quantity of gas produced from both the reactors was ranging from 40 to 200 mL per day. Gas Chromatographic analysis was performed on the gas samples collected from the reactors operating at 6 and 1.5 h HRTs. The gas composition for both the reactors were similar which indicated

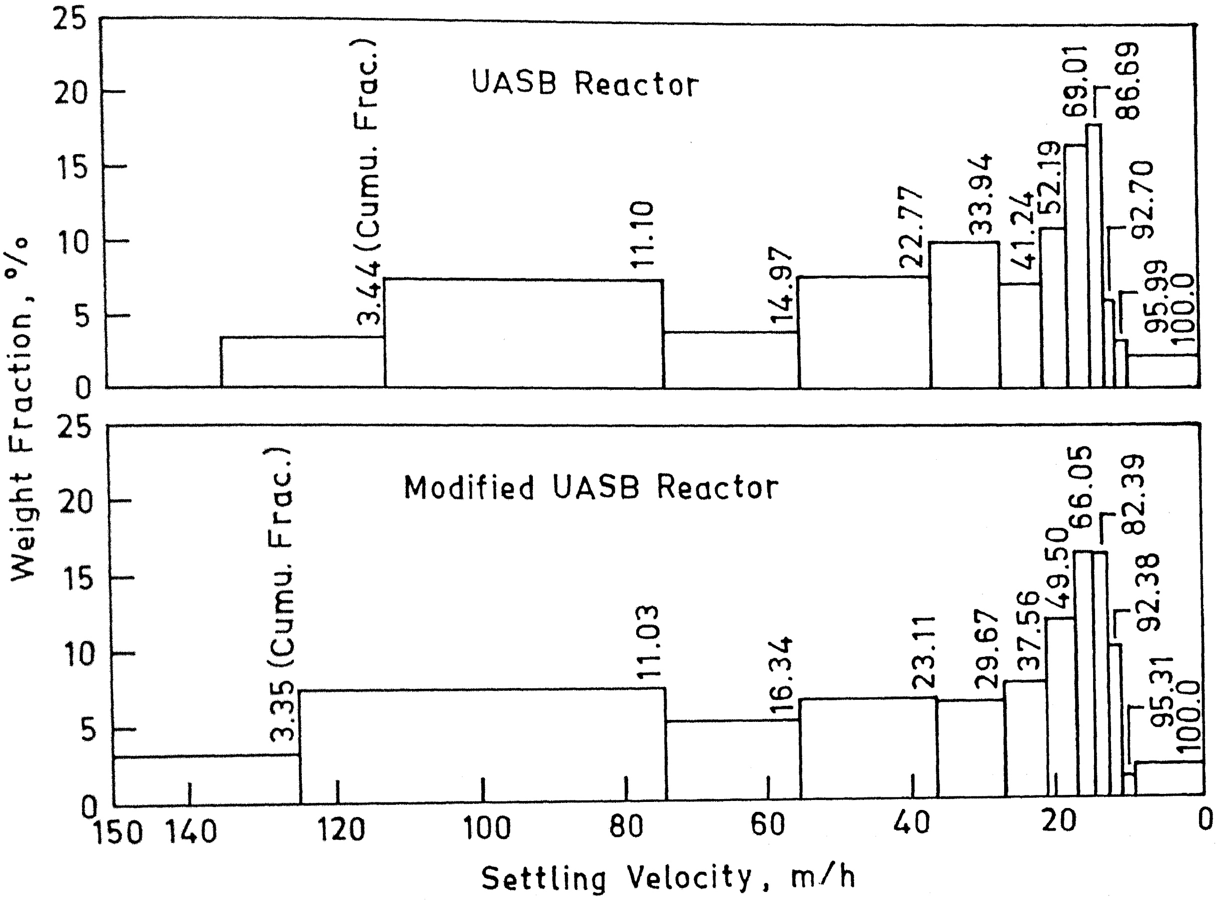


Fig. 5.9. Particle Size Distribution of Granular Sludge as a Function of Settling Velocity.

50-55% methane, 40-45% nitrogen and 4-6% carbon dioxide. The low CO_2 content may be due to its high solubility of CO_2. Similar results were reported by other authors (Lettinga *et al.*, 1983; Kobayashi *et al.*, 1983). Under such conditions, the N_2 fraction becomes significant, constituting the most important volume fraction in the gas phase next to CH_4. The N_2 enters the reactor dissolved in the influent and once in the reactor it is easily stripped by the CH_4 (Noyola *et al.*, 1988). The composition of biogas with HRT at 1.5 h for modified UASB reactor indicated only 28% methane, 69% nitrogen and 3% carbon dioxide.

5.4 Discussion on Comparative Performance of the Reactors

The Organic Loading Rates (OLR) applied to both the reactors during the entire study period are shown in Figure 5.10. The loading started from a low value of 0.768 kg COD/m^3.d at 6 h HRT to the highest value of 2.368 kg COD /m^3.d at 1.5 h HRT. Figure 5.11 shows removals for different parameters at varying OLR. In general, with the increase in OLR, the removals have decreased. However, the removal efficiency of modified UASB is always better than conventional UASB. There was a considerable difference in the TSS removal rates by both the reactors, with a gradual decrease with increase in organic loading. Posterior separation of suspended solids might play an important role in the proper functioning of UASB reactor. However, modified UASB reactor was efficient in removal of TSS.

Due to constant rising of sludge blanket and washout from the UASB reactor, it was not operated after maintaining it at HRT of 2 h. The organic loading was further increased for the modified

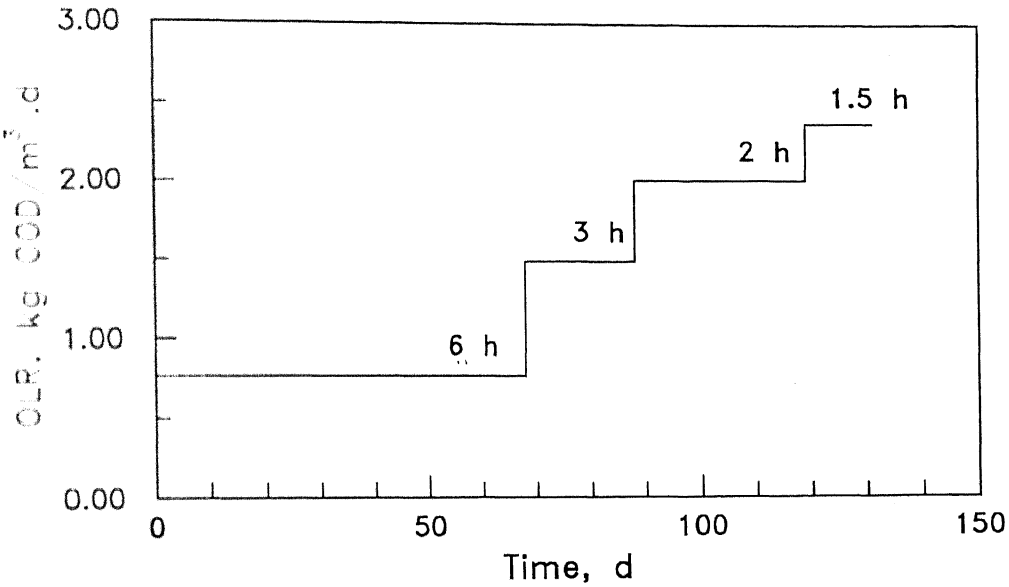


Fig. 5.10 Variation of Organic Loaading Rate (OLR) with Time

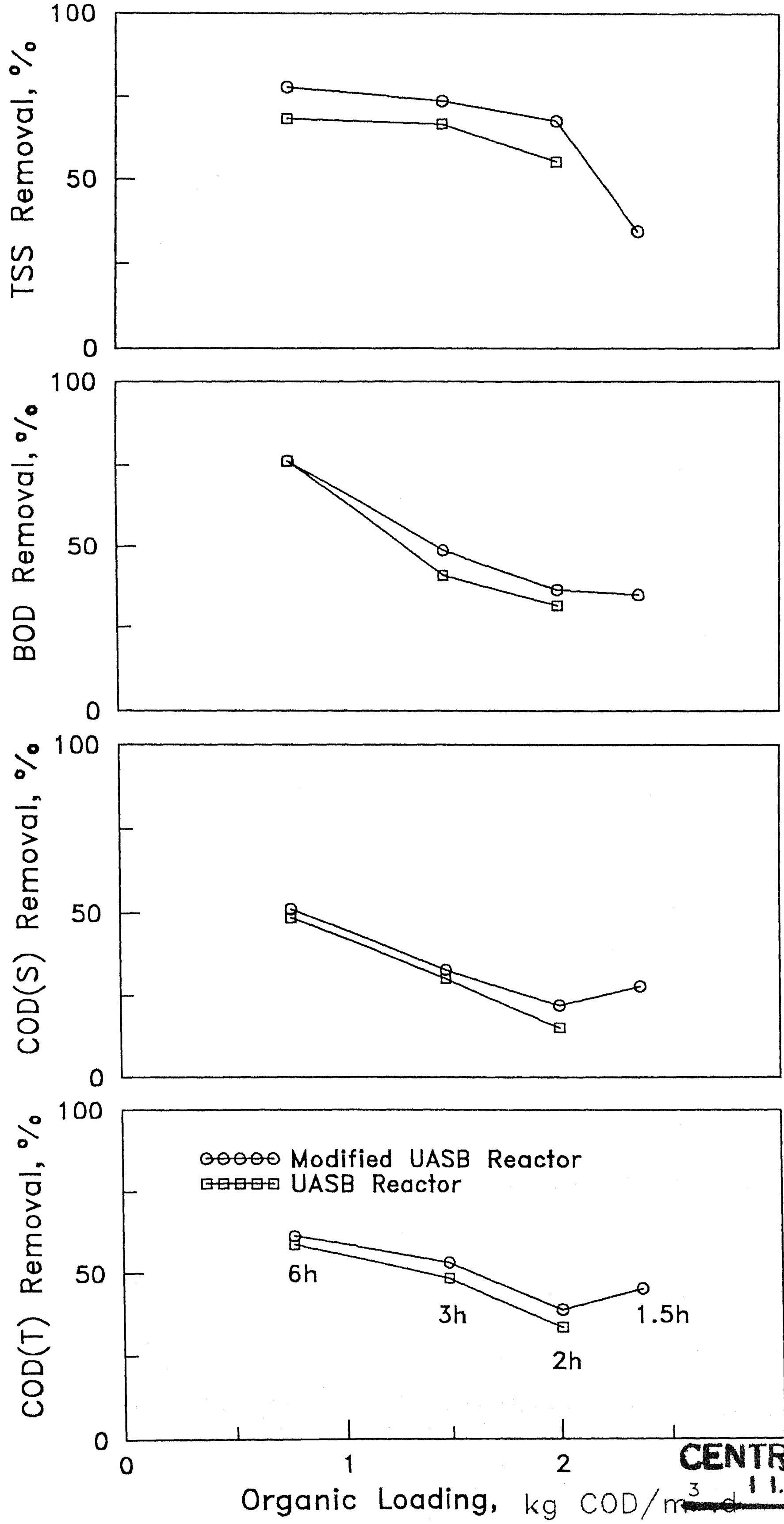


Fig. 5.11 Removal of Parameters with Organic Loading

UASB reactor by decreasing the HRT to 1.5 h. Higher removal of total COD, soluble COD and BOD_5 were obtained at this OLR of 2.368 kg COD/m^3.d compared to 2.004 kg COD/m^3.d. This can be attributed to the expansion of the sludge bed upto the tube settler zone of modified UASB reactor which promoted better contact between the biomass and organic matter. However, the effluent TSS corresponding to this OLR was 114 mg/L which is higher than the permissible value. This appears to be due to escape of smaller and lighter flocculent material alongwith the effluent.

5.5 Role of Tube Settlers

The tube settlers installed in the inclined portion of modified UASB reactor provide a minimum settling velocity of 0.061 m/h corresponding to the HRT of 1.5 h. Referring to the Figure 5.9 for settling velocity distribution of sludge it is clear that the tube settlers were successful in retaining more than 99% of biomass in the reactor. The TSS level of 114 mg/L with HRT of 1.5 h is expected to be consisting of smaller and lighter flocculent materials along with the effluent. Once such materials are removed from the reactor by prolonged operation, it is expected that the modified UASB would meet the TSS standards also.

The TSS and VSS profiles presented in Figures 5.5 to 5.7 show the higher values of TSS and VSS for UASB reactor. Owing to the high hydraulic pressure directly acting on the sludge blanket in the UASB, the sludge blanket appears to be more compressed. This might have increased the entrapment of gas bubbles in the sludge blanket, making it lighter to be lifted up. In the modified UASB reactor, a major portion of this hydraulic head was taken up by

the inclined portion, which resulted in expansion of sludge bed. This expansion eased the release of gas bubbles in modified UASB reactor and hence preventing the lifting of sludge blanket.

6. CONCLUSIONS

The performance of conventional and modified UASB reactors was evaluated in the laboratory employing pregranulated anaerobic sludge and the dilute domestic wastewater as feed. The modified UASB comprised of tube settlers in place of GLSS. The investigation consisted of comparing the performance of reactors during the study period of 131 days by varying the HRTs. The following conclusions may be drawn.

1. The UASB reactors performed well with the inoculated granular sludge.
2. High BOD and TSS removals were exhibited by both reactors when operated at HRT of 6 h so as to meet the standards for disposal. Even at a HRT of 3 h the effluents from both the reactors were of acceptable quality.
3. Washout of granular biomass occured in conventional UASB operating at HRT of 2 h due to lifting of sludge blanket and hence the effluent did not meet the standards especially with respect to TSS. Sludge lifting was absent in modified UASB reactor. The effluent from modified UASB reactor was able to confirm the norms for BOD, while TSS concentration was marginally higher.
4. At a HRT of 1.5 h, the modified UASB reactor showed a higher COD removal than that at 2 h HRT mainly due to the expansion of sludge bed. However, the effluent had higher TSS due to escape of lighter, flocculent and puffy sludge.
5. The Specific Methanogenic Activity (SMA) increased with

decrease in HRT due to increased organic loading rate. Even this loading rate was lower than that for high strength wastewaters. This indicates the capability of granular biomass to sustain the low strength wastewater.

6. The settling characteristics showed that 65% of biomass had settling velocities between 10-30 m/h. The tube settlers in modified UASB reactor is found to be capable of retaining more than 99% of biomass when the reactor was operating at a HRT of 1.5 h.

7. The modified UASB reactor showed a better overall performance in terms of BOD, COD and TSS removals. The role of tube settlers in trapping TSS and reducing the hydraulic pressure acting on sludge bed proved to be very effective.

8. The modified UASB reactor can be used as a package treatment unit to treat low strength domestic wastewater so as to meet the effluent disposal standards for inland waters.

7. SUGGESTIONS FOR FUTURE WORK

Based on this investigation, following suggestions for future work may be proposed.

1. The modified UASB reactor operating at 1.5 h HRT is expected to give a better performance if the lighter, flocculent and puffy sludge is eliminated on prolonged operation. Hence there is a need of further study its performance at a HRT of 1.5 h.
2. Further decrease in HRT can be tried with modified UASB reactor.
3. The optimum dimensions of settler zone (tube settlers) and the optimal number of tubes required, should be determined. This can be done by performing the study with varying the number, diameter, length and angle of inclination of tubes.

REFERENCES

Barbosa, R.A. and Sant' Anna G.L., Jr (1989). Treatment of Raw Domestic Sewage in an UASB Reactor. *Wat. Res.*, **23**, P. 1483.

Dellalo, R. and Albertson, O.F. (1961). Determination of Volatile Fatty Acids by Direct titration. *J. Water Poll. Cont. Fed.*, P. 356.

Fukuzaki, S., Nishio, N. and Nagai, S. (1990). Kinetics of the Methanogenic Fermentation of Acetate. *Appl. Envir. Microbiol.*, **56**, P. 3158.

Genung, R.K., Hancher, C.W., Rivera, A.L. and Harris, M.T. (1982). Energy Conservation and Methane Production in Municipal Wastewater using Fixed Film Anaerobic Bioreactors. *Biotechnol. Bioengng. Symp.*, **12**, P.365. Cited in Mergaert, K., Verstraete, W. and Vanderhaegen, B. (1992). Applicability and Trends of Anaerobic Pre-treatment of Municipal Wastewater. *Wat. Res.*, **26** (8), P. 1025.

Grasius, M.G. (1995). Personal communication, Indian Institute of Technology, Kanpur, India.

Grin, P.C., Roersma, R.E. and Lettinga, G. (1983). Anaerobic Treatment of Raw Sewage at Lower Temperatures. *Proc. European Symposium on Anaerobic Wastewater Treatment (AWWT)*, P. 335, Noordwijkerhout, The Netherlands. Cited in Mergaert, K., Verstraete, W. and Vanderhaegen, B. (1992). Applicability and Trends of Anaerobic Pre-treatment of Municipal Wastewater. *Wat. Res.*, **26** (8), P. 1025.

Gujer, W. and Zehnder, A.J.B., (1983). Conversion Processes in Anaerobic Digestion. *Wat. Sci. Tech.*, **15**, P. 127.

Hulshoff Pol, L.W. (1989). The Phenomenon of Granulation of Anaerobic Sludge. Doctoral Thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

I.I.T., Kanpur Report (1995). Report on Monitoring and performance Evaluation of Ganga Action Plan Phase -I Works, Kanpur.

Jakma, F.F.G.M., Collazos, C.J. and Schellinkhout, A. (1987). Application of Anaerobic Sewage Treatment in Subtropical Countries. *H_2O*, **20** (1), P. 2. Cited in Alearts, G.J., Veenstra, S., Bentvelsen, M. and van Dujil, L.A. (1990). Feasibility of Anaerobic Sewage Treatment in Sanitation Strategies in Developing countries, I.H.E. Report series 20, I.H.E. Delft, The Netherlands.

Joshi, R.N., D'mellow, P., Pai, N. and Naik, M.R. (1988). Pilot Scale Experiment with Anafil Digestor. *IAWPC Tech. Annual*, **15**, P. 77.

Kobayashi, H.A., Stenstrom, M.K. and Mah, R.A. (1983). Treatment of Low Strength Domestic Wastewaters using the Anaerobic Filter. *Wat. Res.*, **17**, P. 903.

Lawrence, P.L. (1969). Kinetics of Methane Fermentation in Anaerobic Treatment. *J. Water Pollution Control Fed.*, **41**, R-1.

Lettinga, G., Roersma, R., Grin P., De Zeeuw, W., Hulshof Pol, L., Van Velsen, L., Hobma, S. and Zeeman, G. (1981). Anaerobic Treatment of Sewage and Low Strength Wastewaters, Cited in *Anaerobic Digestion* 1981, P. 271, Elsevier Biomedical Press, Amsterdam.

Lettinga, G., Roersma, R. and Grin, P. (1983). Anaerobic Treatment of Raw Domestic Sewage at Ambient Temperature using a Granular Bed UASB Reactor. *Biotechnol.* & *Bioengng.*, **25**, P. 1701.

Lettinga, G. and van Haandel, A.C., (1994). Anaerobic Digestion in Sewage Treatment. In *Anaerobic Sewage Treatment*, John Wiley & Sons, Inc.

de Man, A.W.A. and Lettinga, G. (1987). Anaerobic Sewage Treatment at Low Temperatures. *H_2O*, **20**, P. 640. Cited in Alearts, G.J., Veenstra, S., Bentvelsen, M. and van Dujil, L.A. (1990). Feasibility of Anaerobic Sewage Treatment in Sanitation Strategies in Developing countries, I.H.E. Report series 20, I.H.E. Delft, The Netherlands.

Mergaert, K. (1990) Cited in Mergaert, K., Verstraete, W. and Vanderhaegen, B. (1992). Applicability and Trends of Anaerobic Pre-treatment of Municipal Wastewater. *Wat. Res.*, **26** (8), P. 1025.

Mergaert, K., Verstraete, W. and Vanderhaegen, B. (1992). Applicability and Trends of Anaerobic Pre-treatment of Municipal Wastewater. *Wat. Res.*, **26** (8), P. 1025.

Monroy, O., Noyola, A., Ramirez, F. and Guiot, J.P. (1988). Anaerobic Digestion of Waterhyacinth as a Highly Efficient Treatment Process for Develping Countries. In *5th Int. Symp. on Anaerobic Digestion*, 22-26 May 1988, Bologna, Italy, P. 747. Cited in Mergaert, K., Verstraete, W. and Vanderhaegen, B. (1992). Applicability and Trends of Anaerobic Pre-treatment of Municipal Wastewater. *Wat. Res.*, **26** (8), P. 1025.

Noyola, A., Capdeville, B. and Roques, H. (1988). Anaerobic

Treatment of Domestic Sewage with a Rotating-stationary Fixed Film Reactor. *Wat. Res.*, **22**(12), P. 1585.

Pavlostathis, S.G. and Gomez, E. (1991). Kinetics of Anaerobic Treatment : A critical Review. *Critical Reviews in Environmental Control*, **21**(5,6), P. 411.

Prasad, R.S. (1995). A Study on the 36 MLD UASB Plant Treating Tannery Wastewater at Kanpur. M. Tech. Thesis, Indian Institute of Technology, Kanpur, India.

Schellinkhout, A., Lettinga, G., Van Velsen, L., Kooijmans, J.L. and Rodriguez, G. (1985). The Application of the UASB Reactor for the Direct Treatment of Domestic Wastewater Under Tropical Conditions. *Proc. Anaerobic Treatment of Sewage Seminar*, Massachussets, U.S.A. Cited in Barbosa, R.A. and Sant' Anna G.L. Jr (1989). Treatment of Raw Domestic Sewage in an UASB Reactor. *Wat. Res.*, **23**, P. 1483.

Standard Methods for the Examination of Water and Wastewater (1989). (17 Ed.). Jointly published by American Water Works Association, American Public Health Association and Water Pollution Control Federation, Washinton DC.

Tilche, A. and Vieira, S.M.M. (1991). Discussion Report on Anaerobic Filters and Sludge Bed Reactors. *Wat. Sci. Tech.*, **24**, P. 193.

Valcke, D. and Verstraete, W. (1983). A Practical Method to Estimate the Acetoclastic Methanogenic Biomass in Anaerobic Sludges. *J. Water Pollution Control Fed.*, **55**, P. 1191.

Venkobachar, C. (1995). A study on Fate of Fecal coliforms in UASB Plant. *A report submitted to Ganga Project Directorate*, 1995.

Vieira, S. (1988). Anaerobic Treatment of Domestic Sewage in Brazil, Research results and Full-scale Experience. In *Proc. 5th Symp. on Anaerobic Digestion*, Bologna, Italy, P. 185. Cited in Mergaert, K., Verstraete, W. and Vanderhaegen, B. (1992). Applicability and Trends of Anaerobic Pre-treatment of Municipal Wastewater. *Wat. Res.*, **26** (8), P. 1025.